



projektträger
jülich

Status Conference Research Vessels 2026

Conference transcript

Together for innovations
that work

Imprint

„Bibliographic information published by the Deutsche Nationalbibliothek. Die Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.“

Für den Inhalt der einzelnen Beiträge tragen die Autoren die Verantwortung.

Published by

Forschungszentrum Jülich GmbH
Zentralbibliothek, Verlag
52425 Jülich, Germany
Phone: 02461 61-5368
Fax: 02461 61-6103
E-mail: zb-publikation@fz-juelich.de
Internet: www.fz-juelich.de/zb

Edited by and layout

Projectmanagement Jülich, Forschungszentrum Jülich GmbH

Photo credits

p. 5: Barbara Dombrowski

Schriftenreihe Projektträger Jülich Volume 21
ISBN 973-3-95806-890-2

The contributions are abstracts of the results of past research cruises. These results were presented at the Status Conference Research Vessels 2026 at GEOMAR Helmholtz Centre for Ocean Research Kiel.

The complete volume is freely available on the Internet on the Jülicher Open Access Server (JuSER) at www.fz-juelich.de/zb/openaccess.

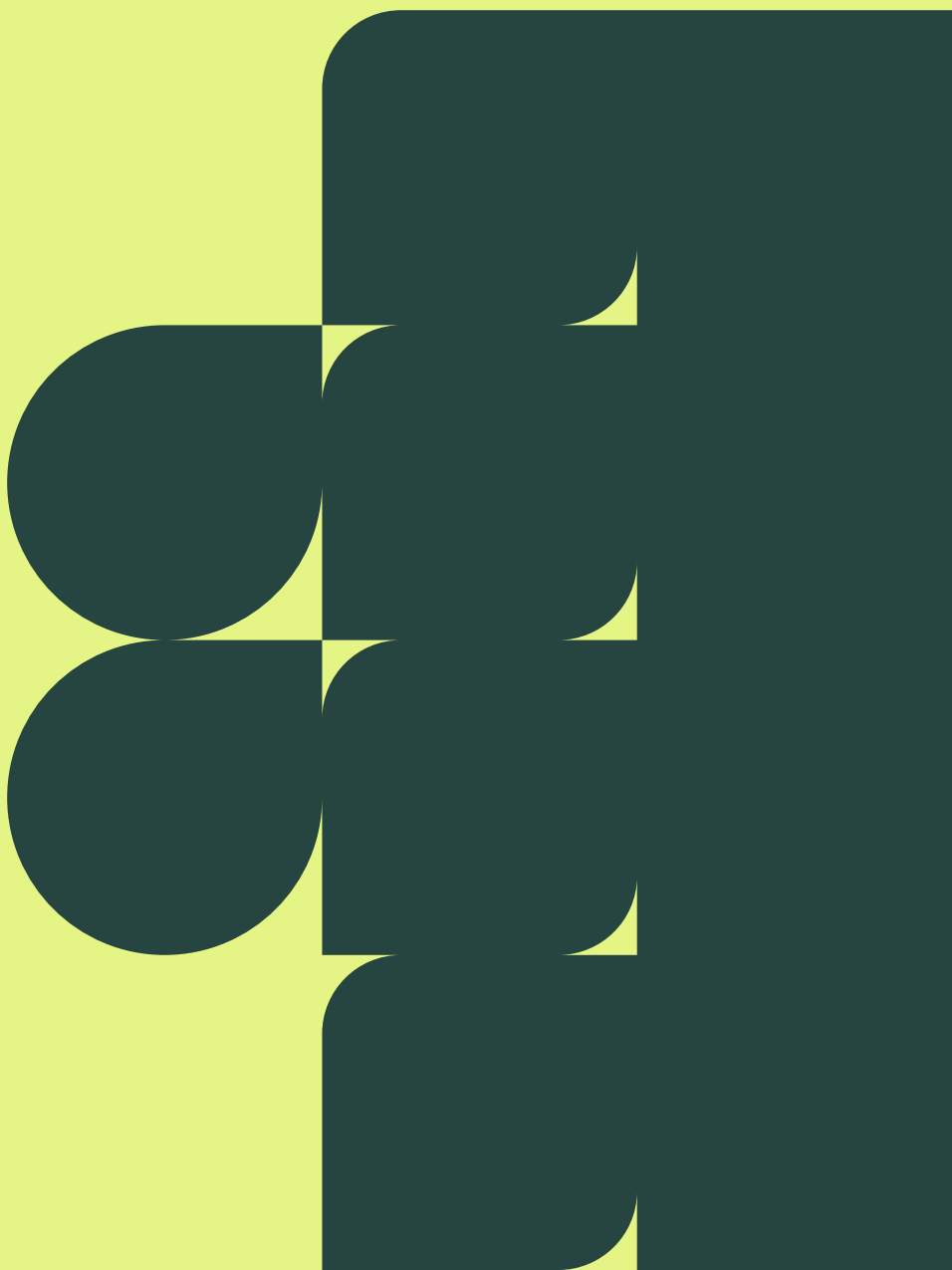
This is an Open Access publication distributed under the terms of the Creative Commons Attribution License 4.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Status Conference Research Vessels 2026

Conference transcript



Foreword



Dear Participants,

it is my pleasure to welcome you to the 4th Status Conference Research Vessels at GEOMAR Helmholtz Centre for Ocean Research taking place in Kiel for the first time.



Exactly 100 years ago the very first research vessel METEOR I was on its expedition on the Atlantic. The crew crossed the Southern Atlantic 14 times and made some groundbreaking discoveries. Their research marked the shift from descriptive oceanography to what we define as analytic oceanography today.

A century later, GEOMAR is about to take over operation of the new METEOR IV in the service to German ocean research. Its state-of-the-art technology and equipment provide the best possible conditions for investigating the ocean and the impacts of climate change at the highest scientific level. We are partnering with the German Research Fleet Coordination Centre for the scheduling of expeditions and Briese Research who will act as ship Manager.

At 125 metres long and with space for 35 scientists and 36 crew members, the new METEOR IV will be a key platform for German ocean research in the Atlantic. The ship can remain at sea for up to 52 days without interruption. Its scientific facilities include 17 laboratories, among them climate chambers and a laboratory for atmospheric chemistry measurements which will allow scientists to investigate the interactions between the ocean and the atmosphere. The vessel is also equipped with high-precision echosounders and research winches that can deploy instruments down to 12,000 metres depth and transmit high-resolution video data to the ship in real time via fibre-optic cable. It offers sufficient capacity to carry large equipment such as ROVs, AUVs or moorings. The ship can maintain an exact position at sampling stations and minimize movements caused by waves.

One of METEOR IV's first major scientific missions will be the one-year FUTURO research campaign off the west coast of Africa. Coordinated by GEOMAR, this international campaign aims to understand how climate change and human pressures are affecting the upwelling ecosystem and thus the livelihoods of people in the region – and how fair, science-based management of the coastal ecosystem can be achieved.

We are delighted to hear about the discoveries made on past expeditions, and we look forward to developing future joint activities that will help us to better understand and safeguard the ocean for future generations.

Prof. Dr. Katja Matthes

Director GEOMAR Helmholtz Centre for Ocean Research Kiel

Table of contents

Foreword	4
Abstracts	18
AL567, AL583, AL590, AL603 and AL615	19
Munition research in the German Baltic Sea – Oct. 2021–July 2024: Results from various projects and cruises	
AL570	31
Baseline study of the impact of bottom trawling on the benthic ecology in the German Baltic Sea	
AL571 and AL592	39
Long-term monitoring of biodiversity changes and their functional consequences in the pelagic ecosystems of the central Baltic Sea	
AL572 and AL576	45
Assessing Environmental Safety of Ocean Alkalinity Enhancement during the 2022 KOSMOS Mesocosm Experiment in Bergen, Norway	
AL573 and AL594	53
RV Alkor expeditions “Baltic Cod, May 2022 and 2023”	
AL575	59
Methane emissions at abandoned wells in the North Sea	
AL586 and AL596	65
North Sea Plastics I & II: Fate and impact of river-borne microplastics and their chemical additives in the North Sea	
AL595	71
New Insights into the Grimsey Hydrothermal Field Offshore Iceland	
AL597	77
Biogeo-optical and -chemical characterization of cyanobacterial blooms in the Baltic Sea for ocean colour satellite remote sensing	

AL611	83
The role of subglacial landforms for offshore freshened groundwater below the southeastern North Sea	
EMB283	91
Vibrio vulnificus proliferation in the Baltic Sea	
EMB286, EMB290, EMB293, EMB298, EMB305, EMB311, EMB314, EMB317, EMB323 and EMB328	97
The state of the Baltic Sea in 2022–2023 – ecosystem variability and long-term changes	
EMB288	105
Trawl marks in the Baltic Sea Basins: Results from Research Cruise EMB288	
EMB292 and EMB319	111
Living along gradients – spatiotemporal variability of macrobenthic communities in the southwestern Baltic Sea	
EMB295	115
Central Baltic Sea Air-Sea Gas Exchange Experiment	
EMB297	119
Hot Spots and Moments of C and N turnover in Planktonic Food Webs at the End of Summer	
EMB306	127
Paleo-Landscapes of the Darss Sill: Results from research cruise EMB306	
EMB315 and EMB347	131
Physicochemical characterization of ship emissions in the atmosphere and Baltic Sea water column	
EMB320	139
Assessing the impact of mobile bottom trawl fishing in marine protected areas (Natura 2000) of the western Baltic Sea, and investigations of bacterioplankton along the salinity gradient of the Baltic Sea (“MGF-Salinity”)	
EMB324	149
Dynamics of redox-sensitive trace metals and biomarkers in the salinity gradient of the Baltic Sea	

HE573, HE584, HE596, HE607 and HE613	155
Risk assessment of war wrecks – a comprehensive approach investigating wrecks containing munitions in the North Sea	
HE590 and HE629	161
RoboLeaks: HE590 and HE629 expeditions	
HE595	165
The Helgoland Mud Area: Understanding Carbon Sinks in Dynamic Shelf Seas	
HE598, HE609, HE614 and HE626	175
Essential Climate Variables in the Ocean's Skin and Near-Surface Layer	
HE601	181
Early stages of the benthic community at the pilot oyster reef in the german north sea	
HE602, HE642 and HE659	187
MGF North Sea II: Effects of the exclusion of bottom-contact fishing on benthic habitats in the Natura 2000 sites 'Sylt Outer Reef' and 'Borkum Reef Ground'	
HE604 and HE625	191
Ecological long-term observation of benthic communities in the German EEZ of the North Sea	
HE605	195
The role and range boundaries of gelatinous zooplankton in the rapidly changing Arctic marginal seas	
HE611	201
Baltic Sea and North Sea Cruise HE611	
HE621	205
Comparison of Modelling and Measurements of GI-Source Sound Propagation in the North Sea	
HE622, HE635 and HE655	211
Legacies of war – assessment of munition hotspots in the German Bight	
HE627	215
FjordChange: Impact of atlantification on ecosystem structure and function in Arctic fjords (Svalbard)	

JC228	219
Seismic structure of fast spreading lithosphere in the Guatemala Basin and the impact of plate bending at deep-sea trenches on the properties of oceanic crust	
MSM105	227
Effects of Variability in Physical Forcing on Carbon and Oxygen Budgets in the Northern Benguela Upwelling System	
MSM107	235
Unravelling Lateral Transport, Organic Matter Transformation, and Seafloor Dynamics on the Irish Continental Margin: Key Results from MSM107	
MSM109	243
Discovery of the first hydrothermal field along the 500-km-long Knipovich Ridge – Results from R/V MARIA S. MERIAN cruise MSM109	
MSM110	249
East Greenland Cruise MSM110	
MSM111	253
Deep drilling in the Baffin Bay for marine sediment records of Greenland Ice Sheet collapse during past warm intervals	
MSM112	267
The Rio Magdalena Delta ROFI system – Land-Sea Interaction of the major tributary of the Caribbean Sea	
MSM112/2	277
Sub-Tropical Atlantic Reference Data	
MSM113	283
First results of Cruise MSM113: Sediment wave generation in continental margins and the structure of the submerged mobile western flank of Cumbre Vieja Volcano, La Palma	
MSM114	291
Time series of benthic oxygen and carbon cycling subjected to enhanced export production driven by mesoscale eddies off West Africa	
MSM114/2	299
Atlantic References and Convection	
MSM115	305
Scientific Results of MSM115	

MSM116	311
MeBo deep-sea drilling on the Stocks Seamount, Equatorial Atlantic	
MSM117	317
Western boundary circulation, flow-topography interaction and ecosystem impacts off Brazil	
MSM118	325
Paleoclimate and Biogeochemistry Nova Scotia 2.0 MSM 118 NOVAMAR 2.0	
MSM119	329
Ridge Flank Observatory Research south of Iceland using seafloor drilling	
MSM120	333
Hudson Bay System Paleoceanography	
MSM122	337
Shaping the structure of fracture zones by magmatic activity at ridge-transform-intersections: constraints from bathymetric and magnetic data	
MSM123	345
Bubble Mediate Gas Exchange in the Labrador Sea (BELS)	
M179	351
Fjord Flux: Dynamic Effects of glacial melting and human impact on fjordic ecosystems of the Beagle Channel and the Chilean fjord system of Southern Patagonia	
M180 and M188	359
Quasi-synoptic observations of energy transfer and turbulence in the ocean: First results of the SONETT experiment	
M181	369
Trans-Atlantic Equatorial cruise II	
M182	379
Role of Eddies in the Carbon Pump of Eastern Boundary Upwelling Systems, REEBUS 01.06.–10.07.2021 Results from cruise M182	
M183	387
Site Survey for Ridge Flank Observatory Science on the Southern Reykjanes Ridge	

M184	395
Process understanding and long-term variability in the Labrador Sea	
M185	403
Assessing Oceanic Impacts on Arrival and Transport of European eel larvae	
M186	409
Azores Hot Vents	
M186/2	415
AtlantIC – Atlantic Trophic Interactions & Carbon Cycle	
M187	419
Biogeochemical dynamics of upwelling filaments in the Benguela	
M189	425
Benguela Niños: Physical Processes in Upwelling Regions and Long-Term Variability	
M190	433
Distribution of Venting Along the Mid-Atlantic Ridge (29–38°N) and Implications for Hydrothermal Exchange and Vent Ecosystems	
M191	439
Submarine volcanism in the western Sicilian Channel	
M192/1 and M192/2	447
BRIDging hydrothermal sites along the HELLenic Arc off Milos from shallow to deep (BRIDGEHELL)	
M193	459
REPLENISH: Red Sea Paleoenvironmental Evolution under Monsoon fluctuations in the Pleistocene to Holocene	
M194	467
Activity, Distribution, and Biodiversity of Hydrothermal Vent Sites in the Red Sea, M194 HEXPLORES	
M195	475
Climate Dynamics and Ecosystem Change during the Rise of Mediterranean Civilizations (CYRTACI)	

M196	479
Gulf of Corinth Groundwater – Is the deep offshore freshened groundwater body within the Gulf of Corinth actively recharging?	
M197	485
Biogeochemistry of the Wintertime Eastern Mediterranean Sea: results from the M197 expedition	
PS124	491
A Continental Shelf Multidisciplinary Flux Study (COSMUS) of carbon	
PS129	503
The expedition PS129 of RV Polarstern in 2022 in the Atlantic sector of the Southern Ocean	
PS131	513
Atlantic Water pathways to the ICE in the Nansen Basin and Fram Strait: Results from the ATWAICE expedition	
PS132	523
North south atlantic training 2022 (oceanapx nosoat)	
PS133/1 and PS133/2	531
“Island Impact” – Understanding the regional impact of islands (South Georgia) on Southern Ocean biogeochemistry and ecosystem function	
PS134	543
Result overview of RV Polarstern expedition PS134 (WAIS-BELL) to the Belling-shausen Sea of West Antarctica in early 2023	
PS135/1 and PS135/2	551
Atlantic transit as a scientific opportunity for interdisciplinary ocean and atmosphere research and WASCAL student training	
PS136 and MSM108	559
Time-Series Studies at the LTER (Long-Term Ecological Research) Observatory HAUSGARTEN	
PS137	571
Exploring Arctic Hydrothermal Vent Fields	
PS138	581
Interdisciplinary long-term observations of a changing Central Arctic Ocean	

PS140	593
EASI-2 East Antarctic Ice Sheet Instabilities – Research Cruise PS140 to the Indian sector of the Southern Ocean and the East Antarctic continental margin	
SO290	599
Paleoceanography and chemical oceanography of the southern Tasman Sea	
SO292	607
ICECARB: Towards an understanding of carbonate platforms in the icehouse world	
SO292/2	619
Characterization and monitoring of serpentinite mud volcanoes' fluid/solid emissions in the Mariana Forearc	
SO293	623
AleutBio (Aleutian Biodiversity Studies)	
SO294	635
CLOCKS: Northern Cascadia extent of locked zone, prism deformation, slip-to-toe, and the edge of subduction & Cascadia CO ₂ : Seismic multi-parameter study at a possible site for CO ₂ storage in basalt in the Cascadia Basin	
SO295	643
Nodule Monitoring 2 – Assessing the environmental impacts of polymetallic nodule mining	
SO296	655
Impact of pelagic Anoxia in the Upwelling Area off Concepción and in a pristine anoxic Fjord, and the postglacial Development of the Patagonian Fjord Region of Chile (MAPUCHE)	
SO297	665
Expedition SO297(PISAGUA): Controlled-source seismic experiments offshore the Atacama Seismic Gap to elucidate structural controls on megathrust slip	
SO289 and SO298	675
GEOTRACES section studies on trace element biogeochemistry in the South and Equatorial Pacific Ocean	
SO299	683
DYNAMET – Arc rifting, metallogeny and microplate evolution: An integrated geodynamic, magmatic and hydrothermal study of the Bismarck Archipelago, Papua New Guinea	

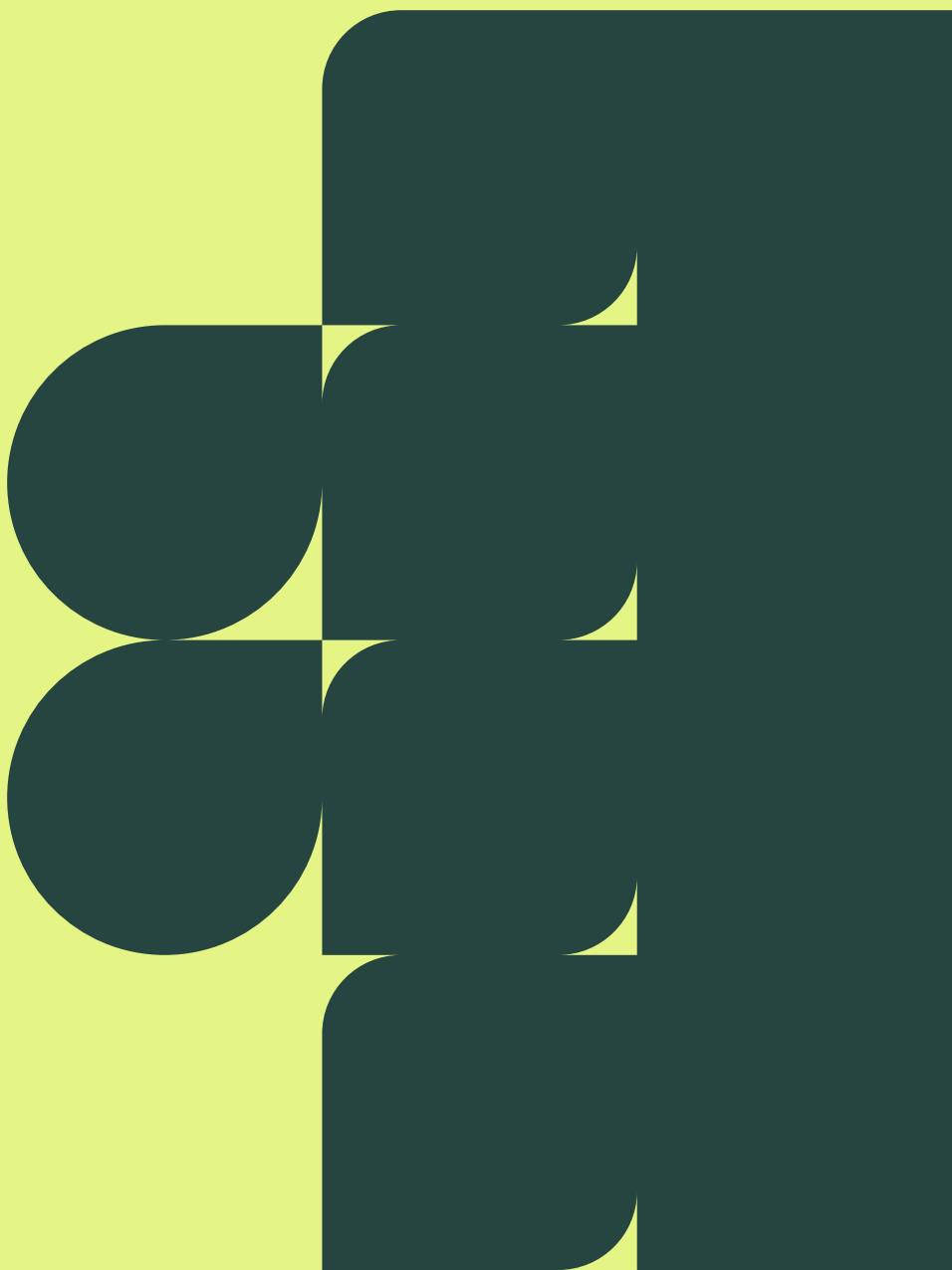
SO299/2	691
Landslide-induced caldera collapse during the 1883 Krakatau eruption	
SO300/1	697
Indian Ocean Exploration for Seafloor Massive Sulphides – INDEX2023 Leg 1 Geophysics	
SO300/2	701
Indian Ocean Exploration for Seafloor Massive Sulphides	
SO301	707
Seismic Imaging at the Central Indian Ridge: Structure and Formation of Oceanic Core Complexes (SCIROCCO)	
Poster	716
HE598, HE609, HE61 and HE626	717
Bridging Surface and Subsurface Salinity Measurements Using Machine Learning	
M190	721
Geochemistry of fluids from hydrothermal systems at the Mid-Atlantic Ridge 29–38°N	
M194	727
Discovery of high-temperature hydrothermalism and massive sulfide formation at Hatiba Mons volcano, Central Red Sea	
MSM111	733
Sea ice and ice sheet dynamics in southeastern Baffin Bay from late MIS 3 to early Holocene: A highly-resolved biomarker study	
MSM111	739
Mixed Turbidite-Contourite Deposits in an Arctic Gateway: New Insights into the Baffin Bay Basin	
MSM111	743
Multiproxy paleoenvironmental reconstruction in the Narsaq Sound over the last 12,000 years	
MSM111	747
Continuous reproduction of planktonic foraminifera in laboratory culture	

MSM120	751
Holocene sea-ice and productivity changes on the Scotian Shelf, NW Atlantic	
PS130/1, PS130/2, PS131, PS132, PS134, PS135/1, PS135/2, PS137, PS140 and MSM111	757
Seafloor mapping and bathymetric data collection by the AWI Bathymetry group in the time period 2022 to 2024	
PS131	763
ICE-Jelly: Influence of sea-ice and sub-mesoscale oceanography on jelly distributions and communities	
PS131	769
WALSEMA during PS131: Water vapor, cloud liquid water and surface emissivity	
PS133/2	775
Natural organic matter coatings on iron oxides shape microbe–mineral–organic carbon interactions in marine sediments	
PS133/2	779
Iron Isotope Constraints on Iron Sources from South Georgia to the Southern Ocean	
PS133/2	783
A Long Shadow of Whaling: Lasting Biogeochemical Legacy in Sediments Near Grytviken, South Georgia	
PS133/2	787
Trophodynamics and Functional Traits in Macrofauna of SG Methane Seeps	
PS133/2	791
Contrasting bioavailability of iron in glacial vs. groundwater to Antarctic phytoplankton: Linking iron uptake to geochemistry (PS133-2)	
SO289 and SO298	795
Cu speciation in the Equatorial and South Pacific Ocean	
SO289 and SO298	801
Distribution and Redox Speciation of Dissolved Vanadium in the South Pacific Ocean and the Equatorial Pacific Ocean	
SO289 and SO298	807
Does dissolved U and Mo show non-conservative depth distributions along two Pacific transects – SO289 and SO298?	

SO289 and SO298	817
High Field Strength Elements (Zr, Nb, Hf): Distributions in the Pacific Ocean from GEOTRACES	
SO289 and SO298	825
Chromium Redox Speciation in Oxygen Minimum Zones in the South (SO289/GP21) and Equatorial (SO298/GP11) Pacific Ocean	
SO289	831
GEOTRACES GP21, Radiogenic Nd Isotopes and Rare Earth Elements in the South Pacific Ocean	
SO290	833
Land-ocean interaction in southern New Zealand during the past 200 ka	
SO290	837
Changes in sea surface temperatures and dust input at the Lord Howe Rise (Tasman Sea) over the past glacial-interglacial cycles	
SO290	841
Bulk properties and biomarker composition of surface sediments from the Tasman Sea	
SO290	847
Dust provenance in the Tasman Sea over the past 140,000 years	
SO293	851
AleutBio – Aleutian Trench Biodiversity Studies	
SO294	855
GEOMAR's Contribution to Deep-Sea Ecosystem Discovery and Management	
SO294	859
Preliminary Interpretation of a Magnetotelluric Profile across the Juan de Fuca Subduction Zone, Results from SO294 CLOCKS.	
SO294	867
Investigating the occurrence and kinematic role of proto-thrusts along the northern Cascadia Margin	
SO294	871
CASCADIA CO2	

SO297	877
Investigating the seismic structure, geometry and seismicity offshore Northern Chile (25°–27.5°S)	
SO299/2	883
Underway bio-optical characterization of surface waters in the Indian Ocean – from Singapore to Mauritius	
SO301	889
Three-dimensional velocity structure of the 25°S Oceanic Core Complex and seismicity at the Rodriguez Triple Junction in the Central Indian Ocean	
SO301	893
From Source to Sink: Complex Dual Role of the Kairei Hydrothermal Plume in Deep Ocean Trace Metal Cycling at the Central Indian Ridge.	
– KABA (Ramifications of Venting at the Kairei Hydrothermal Field for Bathypelagic Microbial Processes in Consort With Carbon and Metal Cycling)	
SO301	901
Seismic Velocity Structure and Segmentation of southwestern Somali Plate along the Central and Southwest Indian Ridges near the Rodrigues Triple Junction	
SO301	905
Methodical Perspectives on SO301 Seismic Data – a Case Study of the Kairei Hydrothermal Fluid Flow System	

Abstracts



AL567, AL583, AL590, AL603 and AL615

Munition research in the German Baltic Sea – Oct. 2021–July 2024: Results from various projects and cruises

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

J. Greinert, A. Beck, M. Kampmeier, M. Seidel, K. Arinaitwe

**Wehrtechnische Dienststelle für Schiffe und Marinewaffen, Maritime Technologie
und Forschung – WTD-71 | Eckernförde, Germany**

H. Schmaljohann, P. Lademann

Senckenberg am Meer | Wilhelmshaven, Germany

Andrey Vedenin, Ingrid Kröncke

Flanders Marine Institute VLIZ | Oostende, Belgium

T. Missiaen, F. Barradas

G-TEC S.A. | Milmort, Belgium

E. Frederickx

Introduction

Marine munition has been a scientific, political, societal and industrial topic for almost two decades now; at first, driven by problems encountered when constructing offshore wind farms and later because the negative effects on the environment were being recognized, e. g. from in-situ detonations and the release of toxic substances from conventional munitions (e. g. TNT, DNB, or RDX) into the environment. Munition entered the marine environment during war activities, but also after the war when Germany was demilitarized and unused munition was disposed of in the Baltic and North Seas. Research related to the five RV ALKOR cruises presented here started in 2016 as part of the UDEMM (<https://udemmm.geomar.de/>) project and continued as part of the BASTA

(<https://www.basta-munition.eu/>), ProBaNNt (<https://www.probannt-munition.eu/>) and Explotect projects. The work undertaken and results gained in these projects finally merged into the CONMAR (<https://conmar-munition.eu/>) project, which is part of the DAM Mission sustainMare (<https://www.sustainmare.de/>). Over the years, the German science community investigating marine munition (both chemical and conventional munition) has been growing together and works hand in glove; it is perceived internationally at the forefront of munition-related studies in Europe, if not worldwide. Today, AWI, GEOMAR, Thünen, Senckenberg, Uni-Rostock, IOW and the Institute for Toxicology and Pharmacology for Natural Scientists at the UKSH are partners in CONMAR and several other EU-funded projects. They cooperate with WTD-71 as well as the Federal Police, the EOD Service of Schleswig-Holstein, GEKA in Munster and the German Navy, some of which are also official partners in various projects.

The five cruises discussed were undertaken from October 2021 to July 2024 as joint cruises of the BASTA and CONMAR projects as part of the MineMoni and MecoMM-BS cruise proposals (Mine Monitoring in the German Baltic, Monitoring ecological consequences of marine munition in the Baltic Sea). All were run by the DeepSea Monitoring group at GEOMAR.

Overarching Objectives

The cruises were conducted to work on the various objectives of the projects involved. Those objectives range from technology-driven tests and method development to reconnaissance multibeam- and AUV-mapping or to investigations regarding the spreading of munition contaminants in the water and sediment. Due to the intense mapping of the munition dumping areas at Kolberger Heide, Falshöft and in the Lübeck Bay area, the acquired data were taken as the basis for deciding which munition pile would be cleared as part of the BMUV/BMUKN Immediate Action Program 'Munitionsaltlasten in Nord- und Ostsee' (<https://www.bundesumweltministerium.de/themen/meeresschutz/munitionsaltlasten-im-meer>). As part of the clearance activities and prior to the start of the clearance activities in August 2024, monitoring measurements around the initial seven sites were carried out on the cruises AL603 and AL615 to investigate the impact of the clearance itself on the marine environment. Table 1 provides an overview of the different objectives worked on during the cruises and which projects they are related to, respectively.

Objectives and related projects	AL567 2021	AL583 2022	AL590 2023	AL603 2023	AL615 2024
Technical developments and test of AUVs with magnetic sensors (BASTA)	X	X	X	X	X
Methodological development of integrating magnetic-AUVs with commercial magnetic survey approaches (BASTA)	X				
Detection of buried munition objects using 3D/ high res sub-bottom profiling (BASTA)	X				
Development and field-testing of on-board mass spectrometer analyses of explosive chemical compounds (Explotect)	X	X	X	X	X
Reconnaissance and inventory mapping of munition objects in the German Baltic sea (BASTA, CONMAR)	X	X	X	X	X
Monitoring the contamination of explosive chemicals in the water column along CTD transects (BASTA, CONMAR)	X	X	X	X	X
Developing methods and best practices of multi-AUV deployments (CONMAR)			X	X	
Investigation of ecological differences between munition contaminated sites and none contaminated sites (CONMAR)			X	X	X
Toxicological studies with mussel moorings to evaluate the uptake of explosive chemicals in fauna (CONMAR)			X	X	X
Co-development activities with stakeholders during the cruise (CONMAR)			X	X	X
Outreach activities to inform the public (CONMAR) and support the Immediate Action Program				X	X
Monitoring studies as part of the BMUV/BMUKN Immediate Action Program				X	X

Table 1: Overview of objectives.

Summary of Cruises

In the following, each cruise is briefly presented to give an overview of the work performed on them. All cruises continued the studies of cruises POS530 (2018) and AL548 (2020), both were part of the MineMoni cruise proposal.

AL567 – October 2021

The main focus of the cruise was placed on the known dumpsites Kolberger Heide and Lübeck Bay, Falshöft (Schleswig-Holstein) and Trollegrund (Mecklenburg-Vorpommern). In each area, high-resolution multibeam mapping was performed and contact lists indicating potential munition objects were produced on board right after data acquisition. Based on those data, AUV surveys were conducted to ground-truth possible contacts via detailed photograph and magnetometer mapping. This was complemented by towed video profiles, SubBottom Profiler (VLIZ Institute) and towed gradiometer surveys (g-tec S.A.). The transits to and between those sites were planned along former constraint routes during WWII (main shipping routes). These routes were main targets of the British Air Force, mines and bombs can be expected to be found along these ways. During transits, water samples were taken with a CTD- (conductivity temperature, depth) and water sampling rosette to obtain a comprehensive data set for munition compounds (inter alia trinitrotoluene (TNT) distribution across the German Baltic Sea. The cruise was supported by the vessel 'Bad Rappenau' of the 3. Minensuchgeschwader/German Navy. During two days, the research vessel ALKOR and the naval unit with their AUV REMUS 100 cooperated to conduct high-resolution sidescan surveys across several pre-defined targets. In addition, navy divers recovered mussel moorings for the Institute for Toxicology. The pre-planned identification of munition objects via navy divers did unfortunately fail due to low visibility.

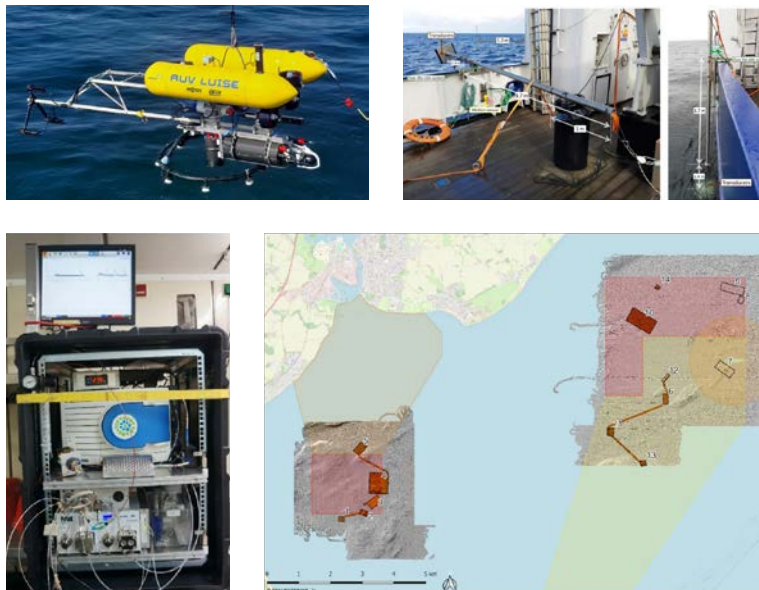


Figure 1: Image impressions of cruise AL567 with AUV Luise, the 3D sub-bottom system installed on a pole, the first version of the Xplotector, and a map of the areas that were mapped by the German Navy using their REMUS AUV in Lübeck Bay.

AL583 – October 2022

The original plan was to work for one week in the North Sea first and have a crew change in Kiel, and then to work in the Baltic Sea. Instead, ALKOR worked in the Baltic Sea supporting the Federal Public Prosecutor General and the Federal Police investigating the NordStream pipelines during the first cruise week. A change of crew took place in Kiel on 18th October and the original Baltic Sea cruise was conducted as planned during the second week. Reconnaissance and mapping several munition dumpsites as well as detailed sediment sampling with Van-Veen grabs around a munition pile in Lübeck Bay were carried out.

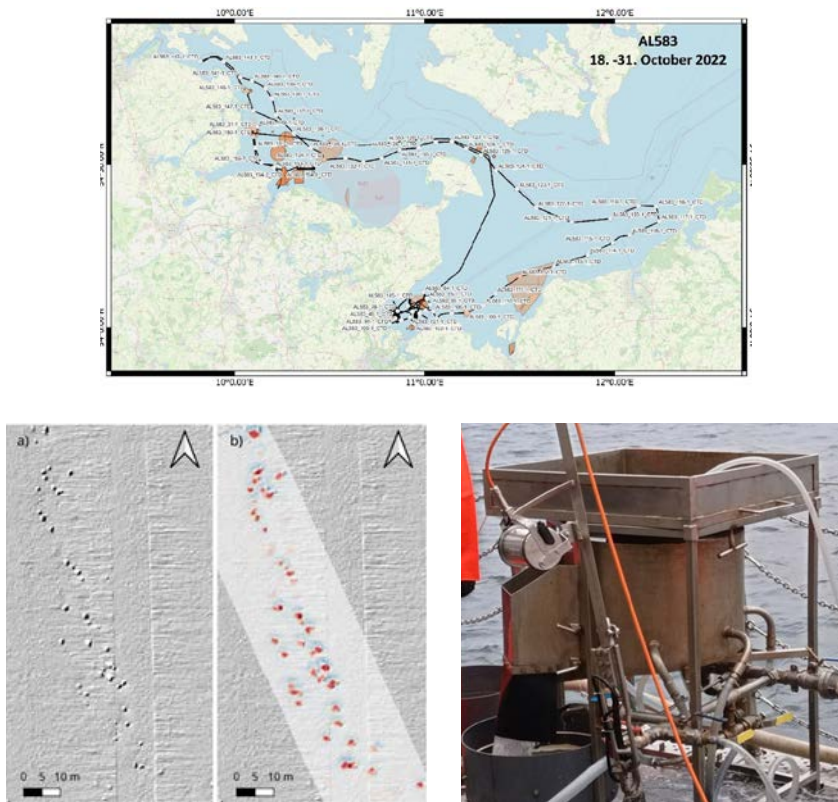


Figure 2: Cruise track of AL583 with CTD stations after the crew change in Kiel. Hillshade bathymetry and its overlay with magnetic data from AUV LUISE at a site with munition objects scattered on the seafloor. Video-guidance set-up for Van-Veen grab sampling in front of the sieving equipment for sediment samples.

AL590 March 2023

During that cruise, ALKOR worked two weeks at the munition dumpsites Kolberger Heide, Falshöft, in Lübeck Bay and west of Rügen. Munition sites were mapped via multibeam, and – for the first time – with a Synthetic Aperture Sonar system installed in the moon pool. Visual inspections with ROV Käpt'n BlauBär and the towed video sled XOFOS supported the reconnaissance work and helped to come

closer to a reliable inventory. Water samples were taken for explosive chemicals and in parallel we sampled the water for eDNA to support eDNA screening within the sustainMare Mission. A change of crew happened on 24th March in Neustadt i. H. with support of the Federal Police to whom we established very good connections based on cruise AL583. In addition to water sampling at three locations we took two lines of each 10 Van-Veen Grabs (twice in Falshöft and once in Pelzerhaken in Lübeck Bay). Additionally, we had AUV SeaOtter of WTD-71 on board which performed low-frequency SAS (LF-SAS) mapping around munition piles to investigate if the extend munition piles continues beyond the visible part on the seafloor surface. LF-SAS does penetrate into soft sediment and can detect buried objects.

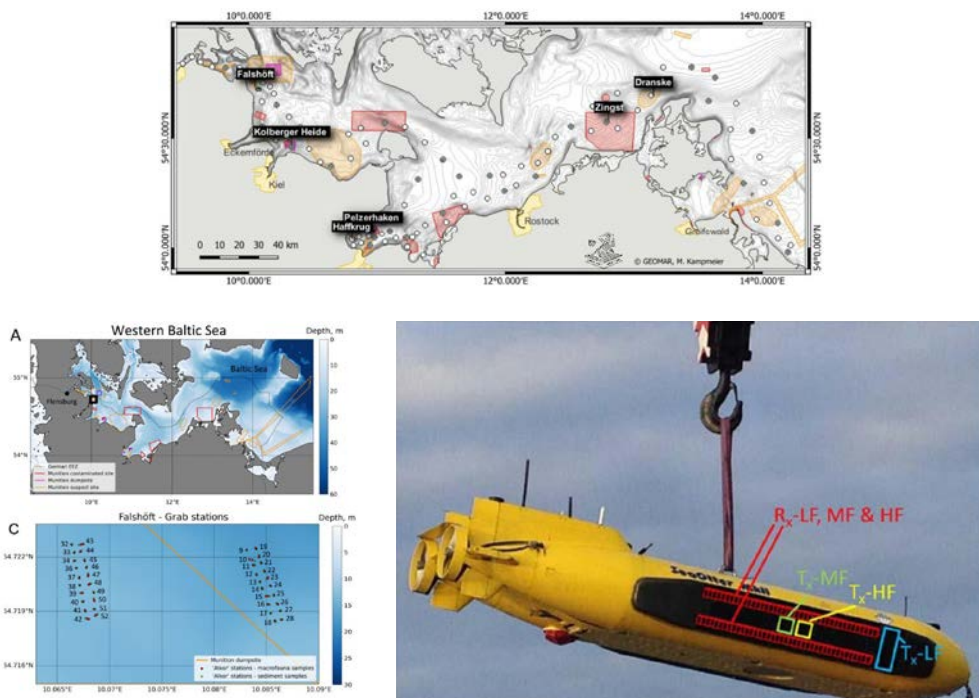


Figure 3: Working areas during AL590 with water samples towards the eastern most part of German waters. Exemplary VanVeen grab stations are shown for the Falshöft working area. AUV SeaOtter with three sets of SAS transducers (LF, MF and HF; low, medium and high frequency; Tx = transmit, Rx = receive).

AL603 October 2023

Cruise AL603 was the second MecoMM cruise and for the first time also studied a munition dumping site in Danish waters near Aarhus and in the Jammerland Bay. One important aim of AL603 was to provide the federal states and the federal government with a clear decision-making aid as to where and how the clearance and final disposal of munitions in the German Baltic Sea should be started and

what negative consequences could be expected on various spatial and time scales if no action is taken. By extending the study to Danish waters, we hoped to gain a better understanding of the distribution of munitions in the area under investigation. Similar to previous cruise the same technology was used with a stronger focus on towed SideScan Sonar using a system supplied by AWI. During this cruise we used the ROV for the first time recover moorings from the seafloor, by attaching a rope to it. This method was refined during later cruises and is now a standard procedure on RV ALKOR. As part of this cruise we also support PhD Patricia Schöntag with addition light absorption measurements using the towed wide sled XOFOS. Great efforts were put in investigating the seven selected clearance sites in Lübeck Bay.

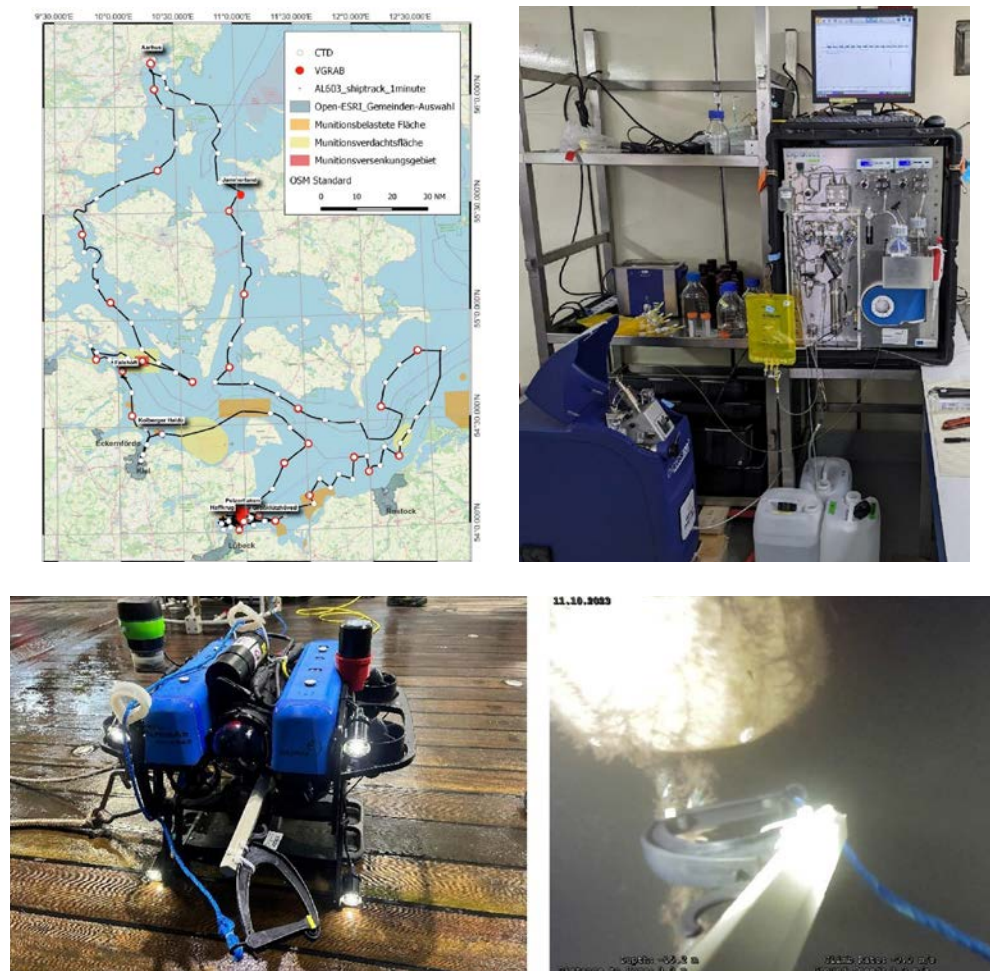


Figure 4: Cruise track of AL603 that also investigated Danish waters. A new version of the Xplotector and ROV Kapt'n BlauBär with its 'Jolly Hook' for catching moorings.

AL615 July 2024

AL615 continued and refined our understanding of the munition contamination particularly in Lübeck Bay. We closed gaps in multibeam data and specifically investigated Fi103 rocket war heads (also known as V1) which presumably are an important source for the strong contamination of the Lübeck Bay area with explosive chemicals. During this cruise we finished establishing working routines for immediate processing of large photomosaiks from images acquired with AUV LUISE or ANTON. In addition, we supported the SAM project to test its true autonomy algorithms on magnetic AUV LUISE which is capable for real-time data interrelation and adaptive mission execution.



Figure 5: Dense point cloud of a photomosaic reconstruction showing an Fi103 rocket war head with 1000kg of explosives when intact. The shown object is open and almost half of the explosives are already dissolved into the water. New version of the ROV mooring recovery hook and a video screen shot showing the recovery of an acoustic current profiler. The hook is placed and pulled out of the deployment arm. ROV and hooked-in device are recovered separately afterwards.

Main Outcomes

It is difficult to link specific outcomes to only one of the above-mentioned cruises. Each cruise builds on data and knowledge gathered during the previous cruises. Over time we acquired a very good understanding of the distribution and type of

munition in the dedicated munition dumping sites of Kolberger Heide, Falshöft and Lübeck Bay. We realized that these areas are the hotspots of munition occurrence on the seafloor with Lübeck Bay being the most contaminated area. We established that munition piles do influence particular the abundance of fauna living next to and on munition objects and showed that all water samples that were taken do have one or more explosive chemical as dissolved contaminant. Currently the data are used to make a 'complete' inventory of location, type and number of munition object, specifically in Schleswig-Holstein waters (which are strongest contaminated). This is done in close cooperation with the Explosive Ordnance Disposal Service of Schleswig-Holstein (Kampfmittelräumdienst) with whom GEOMAR very closely cooperates for several years now. Several papers have been published about the ecological impact, the contamination and the occurrence of munition (see list of publications).

Without these cruises, the Immediate Action Program of BMUV/BMUKN would not have happened. The severity of issue as well as the good data base for deciding where and which pile should be cleared would not have been existing. Without these cruises the excellent knowledge about the issue of marine munition in the German Baltic Sea waters would not exist. These studies have been recognized internationally and supported the willingness of the EU to have more munition-related projects in different funding schemes. GEOMAR established itself as experienced project coordinator is leading two large scale international munition projects at the moment (MMinE-SwEEPER (<https://mminesweeper-munition.eu/>) and CAMMera (<https://cammera-munition.eu/>)).

As part of CONMAR, social sciences and rising public awareness have become additional tasks during our cruises. Many of the cruises had journalist on board who either wrote for local or regional newspapers, came for TV-documentaries or short reports about the problem. All this was able on board of RV ALKOR, strongly supported by the Federal Police who often provide the shuttle service in Lübeck Bay.

With respect to the technical objectives and method development we very much streamlined operations with several AUVs simultaneously in the water and established best practices for on board photomosaic processing. We also generated workflows to start data publications of multibeam data directly on the ship. The Xplotector device is now a robust system that generates results of explosive chemical concentrations with 30 minutes after a sample has been taken. The goal of using AUVs for magnetic mapping could be reached and results of the earlier cruises where used to apply for addition funding for the SAM project. In summery, the German science community investigating marine munition in the Baltic would have the knowledge and international recognition without the series of cruises briefly listed here.

Suitability of RV Alkor

RV ALKOR with its size and technical capabilities and equipment is very well suited for the needed tasks at sea. Despite being not the best on the waves and her sensitivity to wind, decks crew, bridge officers and scientific crew now form a very well operating unit that know each other's competences, know the gear that is used and are knowledgeable in how to operate in munition dumping areas. Jointly they deploy up to four AUVs at the same time, even use large AUVs as the SeaOtter of WTD-71 and GEOMARs AUV-Abyss and are very skilled in operating ROV-BlauBär for visual inspections and recovery of previously deployed mooring (station time for mooring or ADCP recovery is less than 15 minutes). Very accurate positioning is possible down to meter accuracy, which is needed for the sediment and water sampling. Remaining at a location for ROV dives is essential and is performed excellently. RV ALKOR is very well suited for this purpose and also showed its capabilities as part of the NordStream pipeline investigations of the Federal Police in 2022 (AL583).

Scientific Output

List of Publications

Beck AJ, Gledhill A, Gräwe U, Kampmeier M, Eggert A, Schlosser C, Stamer B, Greinert J & Achterberg E, Widespread environmental contamination from relic munitions in the southwestern Baltic Sea, *Chemosphere* 2025, 372, <https://doi.org/10.1016/j.chemosphere.2025.144115>.

Greinert J, Kampmeier M, Buck V & Frey T, Marine Dumped Munition – Example from Luebeck Bay where test clearance will start in 2024, *Hydrographische Nachrichten* 2024, HN128-05, pp 34 – 41, DOI: 10.23784/HN128-05.

Kampmeier M, Michaelis P, Frey T, Seidel M, Wendt J & Greinert J, Workflow towards autonomous and semi-automized UXO Survey and Detection, *Proceedings of Meetings on Acoustics* 2021, Vol. 44, 070025. doi.org/10.1121/2.0001492.

Seidel M, Frey T & Greinert J, Underwater UXO detection using magnetometry on hovering AUVs, *Journal of Field Robotics* 2023, 1-14. <https://doi.org/10.1002/rob.22159>.

Vedenin AA, Kröncke I, Beck AJ, Bodenbinder A, Chrysagi E, Gräwe U, Kampmeier M & Greinert J, Spatial structure and biodiversity of macrofauna around marine munition dumpsites – A case study from the Baltic Sea, Marine Pollution Bulletin 2024, 198. Art.Nr. 115865. DOI 10.1016/j.marpolbul.2023.115865.

Vedenin A, Kröncke I, Beck JA, Arinaitwe K, Bezzubova E, Keller M, Henkel D & Greinert J, Influence of dumped munition on the benthic macrofauna: Relation to munition object proximity and explosive compounds content, 2025, <https://doi.org/10.1016/j.marpolbul.2025.118379>.

von See TB, Greinert J & Meurer T, Detection and tracking of ocean layers using an AUV with UKF based extremum seeking control in the Baltic Sea, Scientific Reports 2024, 14. Art.Nr. 20629. DOI 10.1038/s41598-024-70775-y.

Cruise Reports

AL567: https://doi.org/10.3289/CR_AL567

AL583: https://doi.org/10.3289/CR_AL583

AL590: https://doi.org/10.3289/CR_AL590

AL603: https://doi.org/10.3289/CR_AL603

AL615: https://doi.org/10.3289/CR_AL615

AL570

Baseline study of the impact of bottom trawling on the benthic ecology in the German Baltic Sea

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

D. Clemens, S. Sommer

Leibniz Institute for Baltic Sea Research | Warnemünde, Germany

M. E. Böttcher, M. Gogina, K. Jürgens, J. Piontek, P. Roeser

University of Cologne | Cologne, Germany

H. Arndt, M. Sachs

University of Rostock | Rostock, Germany

S. Forster, M. Janßen

GFZ Helmholtz Centre for Geosciences | Potsdam, Germany

S. Bernsee, J. Kallmeyer

Introduction & objectives

The expedition AL570 with the RV ALKOR (March/April 2022) was carried out within the framework of the interdisciplinary DAM MGF-OSTSEE Project “Potential effects of closure for bottom fishing in the marine protected areas (MPAs) of the western Baltic Sea – baseline observations” funded by the Ministry of Education and Research (BMBF). Within MGF-OSTSEE an interdisciplinary consortium of scientists from various institutions investigated how benthic ecosystems in MPAs within the German exclusive economic zone develop from impacted situation towards an exclusion of bottom trawling. Major goals of the project were i. the initial assessment of the environmental status and its variability in- and outside the three MPAs Fehmarn Belt, Oder- and Rönne Bank under the ongoing pressure of bottom trawling and ii. the assessment of the effect of bottom trawling on benthic communities and benthic biogeochemical functioning. The cruise AL570 concludes a series of three research cruises including the expeditions EMB238 (2020) and EMB267/268 (2021) and aimed to survey all components of the benthic

food web including prokaryotes, protozoans, meiofauna and macrofauna, as well as sediment properties and biogeochemical processes in selected working areas in- and outside of the MPA, Figure 1. Please note that at the time of the cruise, fishing continued within the MPAs. Fishery exclusion from parts of the MPAs occurred in 2024.

The main working areas of the AL570 cruise were the Fehmarn Belt, the Oder Bank and to a minor extent the Rönne Bank. The Oder Bank is the largest and a highly representative sandbank in the German Baltic Sea, mainly located in water depths between 10 and 16 m, composed of well-sorted fine sand. At Oder Bank water dynamics restrict the development of macrophytes, and seafloor mainly consists of bare fine sand.

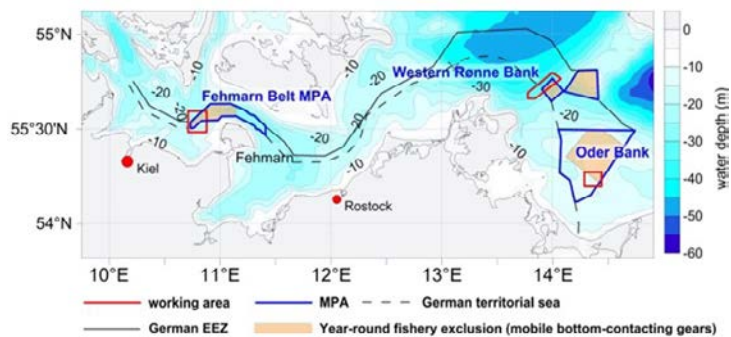


Figure 1: Working areas in- and outside MPAs of the German Baltic Sea during cruise AL570.

Biogeochemical processes in surface sediments

Aim of the geochemical measurements was to study the impact of trawling on sedimentary biogeochemical processes and ecosystem functioning. Sediment samples for porewater (major and trace elements, nutrients, total alkalinity (TA), dissolved inorganic carbon (DIC), $\delta^{13}\text{C}$ -DIC and solid phase geochemistry (P. Roeser, M.E. Böttcher; IOW)) were obtained from two structurally identical GEOMAR BIGO type lander (Biogeochemical Observatory) and in particular the Multiple Corer (MUC) deployments. In situ solute fluxes of oxygen (O_2), nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), phosphate (PO_4^{3-}), silicic acid (H_4SiO_4), TA and DIC (D. Clemens, S. Sommer; GEOMAR) across the sediment water interface were measured using the BIGO I and BIGO II.

Benthic sulfate reduction rates were measured via radiotracers in triplicates in each BIGO chamber during all deployments as well as in sediments retrieved by the MUC by J. Kallmeyer, S. Bernsee (GFZ Potsdam). Microbial sulfate reduction represents the most dominant anaerobic organic carbon degradation pathway in

marine sediments. In reactive surface sediments of the temperate climate zone dissimilatory sulfate reduction can represent an overall high proportion of the entire organic carbon mineralization (Al-Raei et al., 2009; Jørgensen, 1982; 2021).

Comprising previous flux measurements, a mass balance was set up for the Fehmarn Belt for the major biogeochemical processes including stations in- and outside the MPAs, Figure 2. Aerobic respiration accounts for 54% of the total release of dissolved inorganic carbon (mean $24 \text{ mmol m}^{-2} \text{ d}^{-1}$), 10% was due to sulfate reduction the remainder of 36% was caused by carbonate dissolution. Including fluxes measured during EMB238, the total benthic oxygen uptake, which has been shown to be susceptible to bottom trawling (Bradshaw et al. 2021) strongly varied between 10 and $54 \text{ mmol m}^{-2} \text{ d}^{-1}$. A baseline biogeochemical data set of surface sediments in the southern Baltic Sea, characterized by different sedimentology and degrees of disturbance by bottom trawling activity is now provided. Whereas the activity of sulfate reducing bacteria in a mud area were found to be similar during cruise AL570 when compared to previous investigations, substantial differences were observed for sandy sites (Lipka et al., 2018). These may be due to spatial and temporal dynamics in the availability of electron donors and acceptors, e. g. by the impact of sediment disturbance. Porewater gradients represent the net result of superimposing benthic biogeochemical reactions with sediment-water fluxes, and are strongly controlled by the availability of reactive organic matter. The benthic organic matter represents a mixture from land and Baltic Sea sources and is strongly correlated to the abundance of the mud fraction. Microbial activity in the sands is furthermore supported by advective introduction of dissolved organic matter.

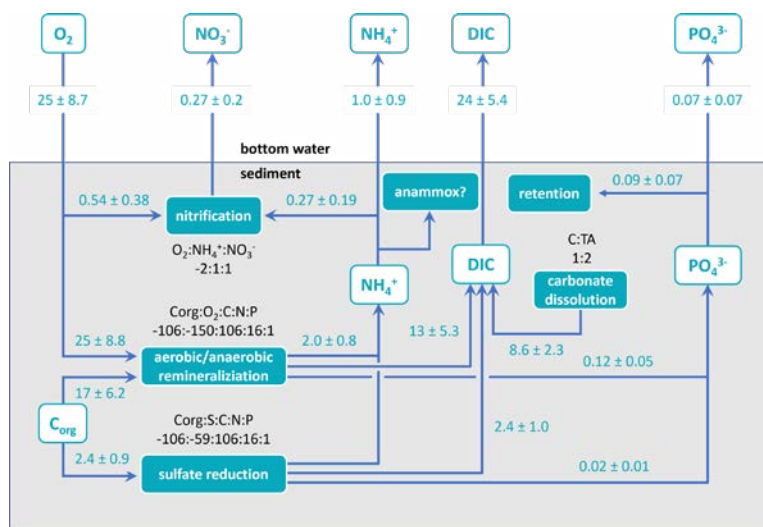


Figure 2: Mass balance of major processes in surface sediments of the Fehmarn Belt including stations in- and outside the MPA.

Benthic ecology

Prokaryotes (J. Piontek, K. Jürgens; IOW) – The main objective of the microbiological working group was to investigate the impact of bottom trawling on the composition and functioning of benthic prokaryotic communities in the Baltic Sea. To achieve this goal stations in the MPAs Fehmarn Belt and Pomeranian Bay – Rönne Bank and a similar number of reference stations near but outside these MPAs were compared. Prokaryotic cell numbers, heterotrophic activity, taxonomic composition and the inventory and expression of functional genes in sediment samples from the surface to 15–20 cmbsf were analyzed. Total prokaryotic abundances were quantified by fluorescence microscopy using a DNA-binding dye. On-board incubations were conducted to estimate rates of extracellular aminopeptidase activity and heterotrophic bacterial biomass production. The taxonomic community composition was analyzed by 16S rRNA high-throughput sequencing. The analysis of gene abundances and gene expression focused on metabolic processes that are important for ecosystem services including carbon remineralization, inorganic nutrient release, and sulfur cycling at the sediment-water interface.

Nano- and Microfauna (M. Sachs, H. Arndt; University of Cologne) – Unicellular eukaryotes comprise the majority of all eukaryotic genotypes in the world's oceans (e. g. de Vargas et al., 2015; Gooday et al. 2020; Schoenle et al., 2021). Protists in the size range of 1–20 µm (nanofauna) and in the size range of 20–200 µm (microfauna) are essential parts of the benthic food web as they channel bacterial production to higher trophic levels (meiofauna, macrozoobenthos), which in turn act as nutritional basis for demersal fish. The bacterial abundance and production is assumed to be regulated by the predation pressure of the nano- and microfauna. Thereby also a variety of geochemical processes mediated by bacteria should be influenced by protists. During cruise AL570, we combined molecular work and work with fixed samples with the live-counting of the delicate protists to analyze the presence also of those protists, which are very sensitive to handling and fixatives or are lacking in GenBank. Living protists at Fehmarn Belt are mostly restricted to the surface layer of sediments during the period of investigation. Former results of eDNA analysis from deeper layers originate mainly from dormant stages. A complex trophic food web connected to the abundant meiofauna taxa could be recorded at Fehmarn Belt. Compared to our earlier data from the Oder Bank one can conclude that the impact of ground fishery might be very different in the different regions of the Baltic Sea due to the different sediment types and the vertical distribution pattern of nano- and microfauna.

Macrozoobenthos (M. Gogina, IOW) – During the cruise AL570 it was continued to tackle temporal changes in the taxonomic and functional composition of the benthic macrofauna community in- and outside the different MPAs. Macrozoobenthos showed substantial variability across sampled areas, stations

within one area, as well as in comparison to results from previous years. As in all visits, among the three studied areas the Fehmarn Belt indicated highest species richness and highest biomass, heavily dominated by the bivalve *Arctica islandica*. Even the position of functional groups in the sediment seem to change with seasons and years. Anthropogenic impact must be considered in the context of environmental variability. This is important for assessing the possible recovery of fauna from trawling disturbance. Based on analysis of combined data comprising 70 stations in the south-western Baltic Sea (including data from AL570), the literature-based hypothesis that less biomass and less sessile benthic macrofauna relates to increased fishing intensity in the biotope type called “aphotic muddy sediment dominated by ocean quahog *Arctica islandica*” was not confirmed. In accordance with the expectations, at stations with high trawling intensity (ICES data) more predators, scavengers, mobile benthic macrofauna, as well as more deep burrowing taxa like polychaete *Scoloplos armiger*, yet in contrast to this hypothesis less priapulids *Halicryptus spinulosus* and more sessile fauna were found. Results also suggested that abiotic factors (like bottom water O₂ concentration, sediment total organic content) have overall more influence on the functional structure than fishing intensity.

Overall, the biogeochemical and biological baseline data obtained during AL570 needs to become interpreted in the context with data sets obtained during previous MGF-OSTSEE, SECOS and later COOLSTYLE/CARBOSTORE cruises. These so-called baseline results measured under the ongoing impact of bottom trawling will strongly contribute to resolve how benthic ecosystems recover from trawling after fishery exclusion from specific areas inside the MPAs.

Acknowledgements

This cruise was approved by the “Gutachterpanel Forschungsschiffe” of the German Research Foundation under license no. GPF 21-1_011.

We highly appreciate the financial support from BMBF, which was granted to GEOMAR and IOW under the IDs 03F0848F and 03F0848A to conduct the project “DAM Pilotmission – Schutzgebiete Ostsee: Auswirkungen des Ausschlusses mobiler grundberührender Fischerei in marinen Schutzgebieten; Vorhaben: Stoffflüsse und Umsatz entlang der Sediment-Wasser Grenzschicht” and the cruise AL570.

References

- Al-Raei AM, Bosselmann K, Böttcher ME, Hespenheide B & Tauber F, Seasonal dynamics of microbial sulfate reduction in temperate intertidal surface sediments: Controls by temperature and organic matter, *Ocean Dynamics* 2009, 59, 351–370.
- Bradshaw C, Jakobsson M, Brüchert V, Bonaglia S, et al., Physical disturbance by bottom trawling suspends particulate matter and alters biogeochemical processes on and near the Seafloor. *Front. Mar. Sci.* 2021, 8, doi: 10.3389/fmars.2021.683331.
- Gooday AJ, Schoenle A, Dolan J & Arndt H, Protist diversity and function in the dark ocean - challenging the paradigms of deep-sea ecology with special emphasis on foraminiferans and naked protists, *European Journal of Protistology* 2020, 75, 10.1016/j.ejop.2020.125721.
- Jørgensen BB, Sulfur Biogeochemical Cycle of Marine Sediments, *Geochemical Perspectives* 2021, doi: 10.7185/geochempersp.10.2.
- Jørgensen BB, Mineralization of Organic-Matter in the Sea Bed – the Role of Sulfate Reduction, *Nature* 1982, 296, 5858, 643–645.
- Lipka M, Woelfel J, Gogina M, Kallmeyer J, Liu, B, Morys, C, Forster S & Böttcher ME, Spatiotemporal dynamics in benthic solute reservoirs of southern Baltic Sea sediments, *Front. Mar. Sciences* 2018, 5, 413, 1–20.
- Schoenle A, Hohlfeld M, Hermanns K, Mahé F, et al., High and specific diversity of protists in the deep-sea basins dominated by diplomonads, kinetoplastids, ciliates and foraminiferans, *Communications Biology* 2021, 4, doi.org/10.1038/s42003-021-02012-5.
- de Vargas C, Audie S, Henry, N, Decelle J, et al., Eukaryotic plankton diversity in the sunlit ocean, *Science* 2015, 348, doi.org/10.1126/science.1261605.
-

Scientific Output

List of Publications

Gogina M, Kröncke I, Marx D & Zettler ML, Status und Trends der biologischen Vielfalt an Küsten und in Küstengewässern. *Zoobenthos*, Wirth C, Bruelheide H, Farwig N, Marx JM & Settele J (Hrsg.), *Faktencheck Artenvielfalt*:

Bestandsaufnahme und Perspektiven für den Erhalt der biologischen Vielfalt in Deutschland, 2024, 681–684,. München: oekom, doi.org/10.14512/9783987263361.

Gogina M, Hahn SJ, Ohde R, Brandt A, et al., Baseline inventory of benthic macrofauna in German marine protected areas (2020–2022) before closure for bottom-contact fishing, *Biology* 2024, 13, doi.org/10.3390/biology13060389.

Piontek J, Schott T, Roeser P, Kallmeyer J, et al., A novel lineage of *Thermodesulfovibrio* contributes to sulfate reduction in sandy sediments of the southern Baltic Sea, (in prep.).

Sachs M, Nitsche F & Arndt H, Cryptic cryptomonads – revision of the genus *Goniomonas*. *J Eukaryot Microbiol* 2025; doi.org/10.1111/jeu.70038.

Sachs M, Dünn M & Arndt H, Benthic heterotrophic protist communities of the Southern Baltic analyzed with the help of curated metabarcoding studies. *Biology* 2023, 12, doi.org/10.3390/biology12071010.

Schönke M, Schulze I, Gogina M, von Dorrien C, et al., What AIS Misses and Acoustics Reveal: Monitoring Seafloor Disturbance and Recovery from Bottom Trawling in the Southern Baltic Sea Over Five Years. doi.org/10.2139/ssrn.5381183 (Preprint, subm.).

List of conference presentations

2024 | **Examining the biogeochemical footprint of bottom-trawling in Baltic Sea sediments.** MGF Seminar 2024, Warnemünde, Germany.

2024 | **EMB238, EMB267 and EMB268. Chasing the signals of bottom-trawling in benthic ecosystems of the western Baltic Sea.** Status Conference Research Vessels 2024, Bremen, Germany.

2024 | **Macrozoobenthos.** Status seminar MGF-Ostsee & MGF-Nordsee Annual meeting 2024, IOW, Warnemünde, Germany.

2024 | **A phylogenetic revision of the widely distributed heterotrophic flagellate *Rhynchomonas nasuta*.** International Meeting of the German Society of Protozoology, Haltern am See, Germany.

2023 | **WP 3.2 Macrozoobenthos: Effects of bottom trawl fishing and its exclusion on benthic macrofauna communities and key species in MPAs of the western Baltic Sea.** MGF Nordsee MGF Ostsee Final Meeting and Kickoff, Bremerhaven, Germany, 25.04.2023.

2023 | **The effects of bottom-trawling on early diagenesis in the Baltic Sea.** Baltic Sea Science Congress (BSSC 2023), Helsinki, Finland.

2023 | **Unexpected survival of various groups of benthic protists at anaerobic conditions.** European Congress of Protistology, Vienna, Austria.

2022 | **Mineral distribution and biogeochemistry of coastal sediments affected by anthropogenic impact of mobile bottom-contact fishing.** International Sedimentology Congress (ISC22), Beijing, China.

2022 | **Field based relationship between cellular sulfate reduction rate and $\delta^{34}\text{S}$ of chromium reducible sulfur in the shallow southern Baltic Sea.** International Sedimentology Congress (ISC22), Beijing, China.

Data

Biogeochemical variables Lander:
GEOMAR repository, to be published June 2026

Biogeochemical variables Sediment:
MGF-DAM project repository, IOW, to be published June 2026

Prokaryotes:
<https://doi.org/10.1594/PANGAEA.961796>

Benthic biology:
MGF-DAM project repository, IOW, to be published June 2026

Macrozoobenthos variables:
IOW database and repository, to be published June 2026

Cruise Report

AL570: https://doi.org/10.3289/CR_AL570

AL571 and AL592

Long-term monitoring of biodiversity changes and their functional consequences in the pelagic ecosystems of the central Baltic Sea

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

J. Dierking, F. Mittermayer-Schmittmann, T. Reusch

Study system and questions

The Baltic Sea is a macro-regional sea under particularly pronounced anthropogenic pressures, including eutrophication, contaminant accumulation, fishing and non-indigenous species, as well as rapid vectors of change, most notably warming and the spread of oxygen minimum zones. It has therefore been identified as a “time machine” reflecting possible multiple-pressure futures of other coastal areas worldwide, and can serve as a test bed for marine environmental management under these conditions (Reusch et al 2018). The Baltic is also characterized by a horizontal salinity gradient from the connection to the North Sea in the west to the freshwater-dominated systems in the north-east. This leads to compositional changes in species pools and food webs along the salinity gradient as marine species “drop out” when they reach their environmental tolerance limits and freshwater species appear in the communities. An overarching question in this system is how ecosystems, communities and species respond to the multiple interacting pressures that are affecting them, and what the underlying mechanism are. Regarding fishes, this concerns e. g., the condition, reproduction, population size and population structure of species. More specific questions include whether warming in the western Baltic Sea has led to match-mismatch of cod larvae with their prey fields, and – focusing on the evolutionary perspective - how local adaptations and adaptation potential determine the fate of species in this system, including the potential presence of rapid fisheries induced evolution. At the conference, we will present answers to some of these questions, based on output linked to the Baltic Sea Integrative Long-term Data Series (BILTS), to which cruises AL571 and 592 contributed.

Concept of the Baltic Sea Integrative Long-term Data Series (BILTS)

Long-term data series have been highlighted as one of the best available tools to separate short-term fluctuations from long-term directional change (Lotze et al 2012), and thus to understand consequences of global change and anthropogenic pressures for biological systems. To address questions regarding the changing Baltic, GEOMAR Helmholtz Centre for Ocean Research Kiel and its precursors have assembled BILTS, one of the best available long-term data and sample series of the pelagic systems of the Baltic Sea, spanning the time period 1986 to the present (Figure 1).

Time series component ¹	1986-1990	1991-1995	1995-2000	2001-2005	2006-2010	2011-2015	2016-2021	2022-2025
Hydrography (T, S, O2 profiles)								
Hydroacoustic data								
Cod single fish data								
Cod otolith samples								
Cod fin clips								
Cod stomachs, gonads								
Liver parasite index								
Stable isotope samples								
Herring, sprat data								
Herring, sprat frost samples								
Zooplankton community samples								
Zooplankton: fish eggs, larvae								
Monitoring gelatinous zoopl.								
Microplastic ²								
Phytoplankton community samples								
eDNA assessments								
PELAGIOS optical survey ³								
Food falls experiments ³								

Figure 1: Parameters included in the Baltic Sea Integrative Long-term Data Series (BILTS) over time.

The concept has been integrative, i. e., combining hydrographic assessments, surveys and sampling of the planktonic system (including fish larvae and jellyfish), and measurements and sampling of key fish species including cod, herring and sprat. The spatial focus has been on the deep, productive Bornholm Basin, home of the largest commercial fisheries in the Baltic, where the same station grid has been covered annually (Figure 2), but since 2021 has also included sampling on a station grid in Kiel and Mecklenburg Bight (western Baltic Sea) to contribute to the West Cod cruise program led by IMF-Hamburg University, as well measurements and sampling along the salinity gradient. The cruises AL571 in April 2022 and AL592 in April 2023 contribute to the long-term data series and West Cod program, but have also included additional, project-based work, including food web sampling for dietary tracer analysis and high-quality tissue sampling for genomic work. At the status conference, we will provide an overview of the outcomes and observations of the 2022 and 2023 cruises, put these new observations in the context of BILTS, and present examples of project applications and insights achieved with this data and sample treasure.

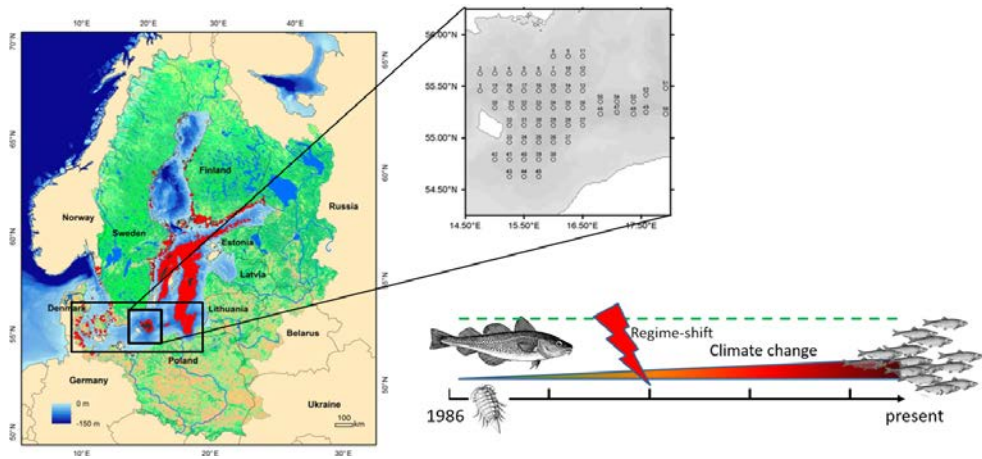


Figure 2: Study system Baltic Sea (left panel) with a close-up of the station grid in Bornholm Basin (cut-out) covered by the cruises AL571 and AL592 in 2022 and 2023, and consistently throughout the Baltic Sea Integrative Long-term Data Series since the year 1986. During the time period 1986 to the present, a regime shift with spreading anoxia in deep water (red areas left panel), a corresponding decline of benthic fauna including the crustacean *Saduria entomon* and a shift from a cod-dominated to a planktivorous fish dominated system took place in the study area (depicted in the bottom right). Both cruises also covered additional stations in the Kiel and Mecklenburg Bight (western Baltic Sea) to contribute to the West cod cruise program by IMF-Hamburg University, and additional stations in the Arkona Basin and Gdansk Deep to cover part of the salinity gradient of the Baltic Sea.

Project applications and insights achieved

We will focus on two core lines of work and output, (1) the biology of Baltic cod in the context of recent stock collapse and environmental changes, including examples for use of data in stock assessments, and (2) trophic interactions and food web positions of common Baltic Sea fish and jellyfish species under changing environmental pressures. More output linking to BILTS samples, including one of the first studies providing evidence for rapid fisheries induced evolution in a fish stock in the wild, will be presented in the complementary talk on cruises AL573 and AL594 at this conference.

References

Lotze HK, Sea of Plenty? Historical trends, current issues, and future perspectives on our use of seafood, in Food For Thought: A Multidisciplinary Discussion, Stewart RS & Korol SA., Editors. 2012, Cape Breton University Press.

Reusch TBH, Dierking J, Andersson HC, Bonsdorff E, Carstensen J, Casini M, Czajkowski M, Hasler B, Hinsby K, Hyytiäinen K, Johannesson K, Jomaa S, Jormalainen V, Kuosa H, Kurland S, Laikre L, MacKenzie BR, Margonski P, Melzner F, Oesterwind D, Ojaveer H, Refsgaard JC, Sandström A, Schwarz G, Tonderski K,

Winder M & Zandersen M, The Baltic Sea as a time machine for the future coastal ocean, Science Advances 2018, 4: eaar8195.

Scientific Output

List of Publications

Eglite E, Mohm C & Dierking J, Stable isotope analysis in food web research: Systematic review and a vision for the future for the Baltic Sea macro-region, Ambio 2023, 52. DOI 10.1007/s13280-022-01785-1.

Han KY, Brennan RS, Monk CT, Jentoft S, Helmerson C, Dierking J, Hüsey K, Kokubun EE, Fuss J, Krause-Kyora B, Thomsen TB, Heredia BD & Reusch TBH, Genomic evidence for fisheries-induced evolution in Eastern Baltic cod. Science Advances 2025, 11 (26), Art.Nr.: eadr9889, DOI 10.1126/sciadv.adr9889.

Helmerson C, Weist P, Briec MSO, Maurstad MF, Schade, FM, Dierking J, Petereit C, Knutsen H, Metcalfe J, Righton D, André C, Krumme U, Jentoft S & Hanel R, Evidence of hybridization between genetically distinct Baltic cod stocks during peak population abundance(s), Evolutionary Applications 2023, 16, 1359–1376.

Kokubun EE, Eastern Baltic cod (*Gadus morhua*) mtDNA diversity through time (MSc thesis 2022), Christian-Albrechts-Universität zu Kiel, Kiel, Germany, 53 pp.

Stoltenberg I, Mittermayer FH, Clemmesen C, Dierking J & Javidpour J, Predation on Baltic sea yolk-sac herring larvae (*Clupea harengus*) by the invasive ctenophore *Mnemiopsis leidyi*, Fisheries Research 2024, 273, 106973, DOI 10.1016/j.fishres.2024.106973.

Stoltenberg I, Trophic ecology and food web interactions of Baltic Sea jellyfish, PhD thesis 2022, Syddansk Universitet (SDU), <https://doi.org/10.21996/zeek-hy62>.

List of conference presentations

2023 | **Trophic interactions in the rapidly changing western and central Baltic Sea** Invited presentation at the Stockholm University DEEP seminar series, Stockholm, Sweden.

2023 | Gezielte Maßnahmen oder Blindflug – was wissen wir über die westliche Ostsee, und welche Rolle spielt dies für den geplanten Nationalpark Ostsee?

Invited presentation at the Runder Tisch Meeresforschung Schleswig-Holstein, Umweltministerium Schleswig-Holstein, Kiel, Germany.

2023 | Meeresschutz und die Ostsee-Zeitmaschine – welche Lehren

wir aus dem Randmeer vor unserer Haustür ziehen können. Visit of the “Meeresschutzbeauftragte” of the German federal government, Kiel, Germany.

2024 | Was hilft der Ostsee? Marine Schutzkonzepte in der Diskussion.

podium discussion organized by Enjust, Center for Ocean and Society and Kiel Marine Sciences, Kiel, Germany.

Data

AL571 and 592 cruise data collection in the GEOMAR OSIS repository:

<https://osis.geomar.de/app/expeditions/359858/links>

<https://osis.geomar.de/app/expeditions/363078/links>

Genetic data:

NCBI/Genbank:

NCBI BioProject PRJNA1128530

Physical oceanography data:

Hinrichsen HH, Reusch TBH, Dierking J, Lehmann A (2025): Time series of physical oceanography in the Baltic Sea from 2011-2022 [dataset publication series].

PANGAEA, <https://doi.pangaea.de/10.1594/PANGAEA.979407>

AL592: Schlundt M, Dierking J, Mittermayer, FH (2024):

Continuous thermosalinograph oceanography along RV ALKOR cruise track AL592.

PANGAEA, <https://www.pangaea.de/?q=campaign%3A%22AL592%22>

Cruise Reports

AL571: https://doi.org/10.3289/CR_AL571

AL592: https://doi.org/10.3289/CR_AL592

AL572 and AL576

Assessing Environmental Safety of Ocean Alkalinity Enhancement during the 2022 KOSMOS Mesocosm Experiment in Bergen, Norway

Authors

Southern Cross University | Lismore, Australia
K. Schulz

GEOMAR Helmholtz Centre for Ocean Research | Kiel, Germany
U. Riebesell, L. Kittu

Background

To limit climate change to well below 2°C in comparison to pre-industrial times, active measures are required to remove carbon dioxide (CO₂) from the atmosphere. Among ocean based approaches, ocean alkalinity enhancement (OAE) has the largest potential. It speeds up the natural process of alkaline rock weathering on land which governs atmospheric CO₂ levels on geological timescales. Directly adding alkaline materials (often containing calcium and silicate) to seawater increases surface water alkalinity which leads to shifts in carbonate chemistry speciation (Schulz et al. 2023), such as e. g. increasing pH as well as decreasing partial pressure of CO₂ (pCO₂). The latter drives additional atmospheric CO₂ uptake until an equilibrium is reached again. Depending on the alkaline material, alkalinity release and changes to carbonate chemistry speciation can be instantaneous, while CO₂ re-equilibration, which would also bring pH close to initial levels, is on the order of months to years. Hence, organisms might experience relatively low pCO₂ and high pH conditions over extended periods of time, particularly close to point sources. Therefore, it is paramount to assess potential impacts on marine ecosystems and the services they provide.

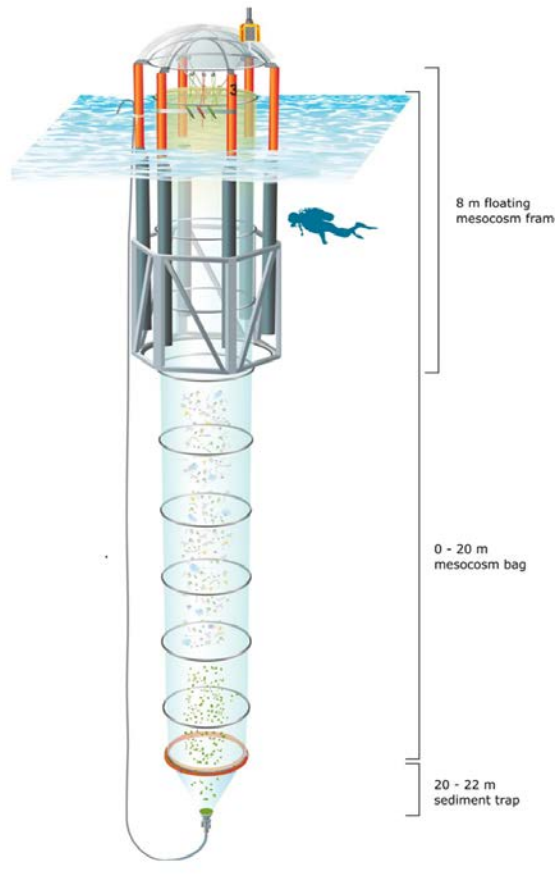


Figure 1: Conceptual diagram of a KOSMOS mesocosm setup.

The KOSMOS mesocosm infrastructure (Figure 1) offers the unique opportunity to test responses of entire natural pelagic communities to changes in seawater chemistry (Riebesell et al. 2013), either driven by climate change or potential mitigation strategies such as OAE. Hence, R/V ALKOR was used during AL572 to bring 10 KOSMOS mesocosms from Kiel, Germany, to Bergen, Norway, where they were deployed in the Raunefjorden, while during AL576 they were recovered and brought back to Kiel.

Experimental Setup

After mesocosm deployment and mooring, the 20 m long mesocosm bags were extended to depth, and at the top submerged about 1m below the surface, as well as covered with a 3mm mesh at both ends to allow seawater exchange while excluding larger organisms. After 5 days, the sediment traps were attached to

the bottom and the top was secured 1 m above the water surface to the floating frames, marking the beginning of the experiment on the 13th of May 2022. Calcium- and silicate-based OAE were simulated using respective alkaline solutions, and manipulations of 4 mesocosms each were carried out on day 4, creating an alkalinity gradient in steps of 150 $\mu\text{mol kg}^{-1}$ from +0 to +600 $\mu\text{mol kg}^{-1}$ (Figure 2). Sampling was conducted daily for the first 3 days, and then changed to every other day for the remaining 50 days of the experiment.

A wide range of sampling parameters was covered, including water column dissolved and particulate matter, dissolved inorganic nutrients, carbonate chemistry speciation, phyto- and zooplankton diversity and abundance, fish larvae growth, as well as organic matter flux to the sediment traps. Half-way through the experiment dissolved inorganic nutrients were added to simulate the upwelling of deeper water layers (see Schneider et al. 2025 for details on the experimental setup).

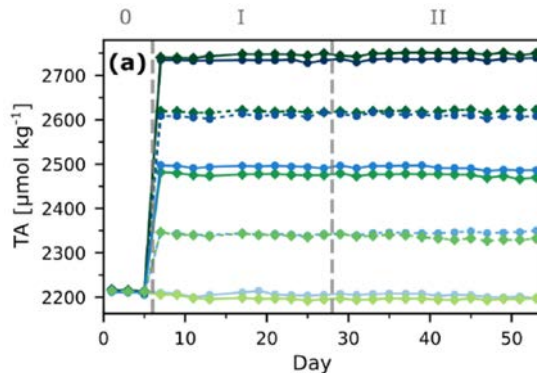


Figure 2: Temporal development of total alkalinity (TA) concentrations in the 10 mesocosms. Green and blue colours depict the silicate- and calcium-based treatments, respectively, while increasing colour intensity highlights increasing TA.

Selected Results

Following TA manipulations, there was a continuous influx of atmospheric CO_2 into the mesocosms, which was higher the more total alkalinity (TA) had been added (Figure 3). Most watercolumn parameters such as Chla or particulate organic matter did not show significant responses to OAE, or differences between the silicate and calcium treatments. This fits to metabolic rate incubations which also showed little effect to OAE (Marin-Samper et al. 2025). In contrast, phytoplankton community responses to OAE were strongly group-specific and shaped by nutrient availability. The initial phytoplankton community was dominated by nano- and picoplankton, with coccolithophores contributing modestly and diatoms occurring

at the lowest abundances across all treatments. Under nutrient-limited conditions, most groups were largely insensitive to both mineral and TA, with the exception of coccolithophores, which declined with increasing alkalinity in the silicate-based treatment. Following nutrient addition, coccolithophore abundances increased rapidly in intermediate TA treatments exhibiting an optimum response along the alkalinity gradient with peak abundances at ΔTA 150 and 300 $\mu\text{mol kg}^{-1}$. This optimum curve response was also observed for overall net community calcification (Schneider et al., 2025). Diatom abundances were higher in the silicate-based OAE and showed an increasing trend with increasing TA in a non-linear pattern. Their response to nutrient addition was however delayed with increasing TA, and they only outcompeted coccolithophores at the highest alkalinity levels (ΔTA 450 and 600 $\mu\text{mol kg}^{-1}$) where $p\text{CO}_2$ dropped below 100 μatm (Figure 4). Additional results include the finding that diatom cellular silicification was also, for the most part, not affected by OA, with the exception of two species. However, watercolumn and sediment biogenic silica concentrations were generally higher in the silicate- in comparison to the calcium-based OAE treatments (Ferderer et al. 2024).

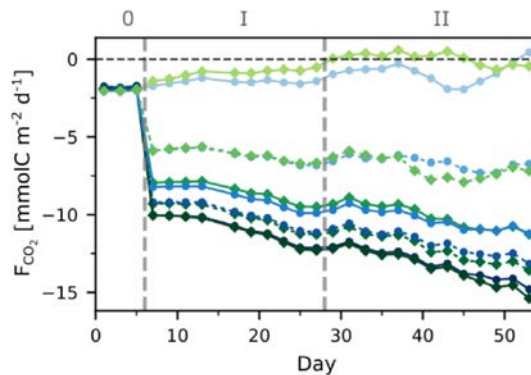


Figure 3: Daily CO_2 flux over the experimental period. Negative values show ingassing. For colour-coding see Figure 2.

In contrast, in-situ net community production based on air-sea gas exchange- and calcification-corrected changes in dissolved inorganic carbon was higher in the silicate-based OAE treatments than in the calcium ones, indicating a significant mineral affect on diatom productivity (Schneider et al. 2025). This is in line with the ‘green-ocean’ hypothesis (Bach et al. 2019) which suggested that silicate-based OAE could enhance diatom primary productivity at the expense of other phytoplankton groups such as calcifying coccolithophores. However, in our experiment this green shift emerged only after nutrient addition and conditions where coccolithophore abundances declined after their peak or at high alkalinity (ΔTA 450–600 $\mu\text{mol kg}^{-1}$). This suggests that the expression of the green-ocean

hypothesis not only depends on mineral type, but also degree of alkalinity increase, nutrient regime and community stage/succession.

Additionally, coccolithophores were hypothesised to, in turn, profit from calcium-based OAE. However, this is opposite to what was observed here, i. e. coccolithophore calcification and abundances were mostly negatively affected by OAE, following an optimum curve response to carbonate chemistry changes (Schneider et al. 2025).

Finally, despite strong chemical perturbations, zooplankton remained unaffected, indicating a notable tolerance to CO₂-unequilibrated OAE conditions (Sánchez et al. *subm.*). Fish larvae biomass, which was collected at the end of the experiment using a net of the same diameter as the mesocosms, appeared to be positively influenced by OAE (with no mineral effect), which was surprising, given the responses described above (Goldenberg et al. 2024).

In conclusion, the planktonic communities were mostly resilient, with only minor effects, to the two OAE approaches tested here. This suggests that within the here applied alkalinity range (up to +600 µmol kg⁻¹) both tested OAE approaches have relatively little environmental impact.

References

Bach LT, Gill SJ, Rickaby REM, Gore S & Renforth P, CO₂ Removal with Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for marine Pelagic Ecosystems, *Frontiers in Climate* 2019, 1, doi: 10.3389/fclim.2019.00007.

Schulz KG, Bach LT & Dickson AG, Seawater carbonate system considerations for ocean alkalinity enhancement research, *State Planet* 2023, doi:10.5194/sp-2-oae2023-2-2023.

Riebesell U, Czerny J, van Bröckel K, et al., A mobile sea-going mesocosm system – new opportunities for ocean change research, *Biogeoscience* 2013, 10, 1835–1847. doi, 10.5194/bg-10-1835-2013.

Van Vuuren DP, Stehfest E, Gernaat, et al., Alternative pathways to the 1.5°C target reduce the need for negative emission technologies, *Nature Climate Change* 2018, 8, 391–397, doi:10.1038/s41558-018-0119-8.

Scientific Output

List of Publications

Ferderer A, Schulz K, Riebesell U, et al., Investigating the effect of silicate- and calcium-based ocean alkalinity enhancement on diatom silicification, *Biogeoscience* 2024, 21, 277-2794, doi:10.5194/bg-21-2777-2024.

Goldenberg SU, Riebesell U & Brüggemann D, Early life stages of fish under ocean alkalinity enhancement in coastal plankton communities, *Biogeoscience* 2024, 21, 4521-4532, doi:10.5194/bg-21-4521-2024.

Marin-Samper L, Aristegui J, Hernandez, N & Riebesell U, Responses of microbial metabolic rates to non-equilibrated silicate- versus calcium-based ocean alkalinity enhancement, *Biogeoscience* 2024, 21, 5707-5724, doi:10.5194/bg-21-5707-2024.

Sánchez N, Schulz K, Goldenberg S, et al., submitted to *Communications Earth & Environment*, Zooplankton responses to ocean alkalinity enhancement under contrasting food web conditions.

Schneider J, Riebesell U, Moras CA, et al., Air-sea gas exchange measurements helped derive in-situ organic and inorganic carbon fixation in response to Ocean Alkalinity Enhancement in a temperate plankton community, *Biogeoscience Discussion* 2025, doi:10.5194/egusphere-2025-524.

List of conference presentations

2024 | **Responses of phytoplankton community to silicate-based and calcium-based ocean alkalinity enhancement**, EGU General Assembly, Vienna, Austria.

2024 | **Assessing the impact of ocean alkalinity enhancement on the zooplankton community**, Workshop for Maritime Technologies, Helgoland, Germany.

2024 | **Plankton Food Webs under Ocean Alkalinity Enhancement**, AGU Ocean Science Meeting, New Orleans, USA.

2023 | **Assessing the Response of Suspended Particulate Matter Stoichiometry to Ocean Alkalinity Enhancement (OAE)** EGU General Assembly, Vienna, Austria.

Data

Carbonate Chemistry:

<https://doi.pangaea.de/10.1594/PANGAEA.983061>

Diatom Silicification:

<https://doi.org/10.25959/G3FN-HE45>

Fish abundance, biomass and sedimentation:

<https://doi.org/10.1594/PANGAEA.967059>

Phytoplankton metabolic rates:

<https://doi.org/10.1594/PANGAEA.972371>

Cruise Reports

AL572: <https://www.fiskeridir.no/english/coastal-management/marine-scientific-research/cruises-2022/alkor-cruisereport-03052022-11052022.pdf>

AL576: <https://www.fiskeridir.no/english/coastal-management/marine-scientific-research/cruises-2022/alkor-cruisereport-16072022-25072022.pdf>

AL573 and AL594

RV Alkor expeditions “Baltic Cod, May 2022 and 2023”

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany
T. Reusch, J. Dierking, F. Mittermayer-Schmittmann, K. Han

The RV ALKOR expeditions “cruise AL573” in 2022 and “cruise AL594” in 2023, both titled “Baltic Cod,” focused on assessing the status of the Eastern Baltic cod (*Gadus morhua*) stock, its prey fields (zooplankton and pelagic fish prey), and the hydrographic baseline conditions of the western and central Baltic Sea. Together, these cruises extended a long-term ecological time series on the composition and functioning of the Baltic Sea ecosystem at GEOMAR, reaching 37 years in 2022 and 38 years in 2023, with particular emphasis on the deeper basins. Both expeditions contributed to ongoing research within the Research Unit Marine Evolutionary Ecology (EV) at GEOMAR, notably supporting the DFG-funded Research Training Group (RTG) Translational Evolutionary Research and its subproject “Fisheries Induced Evolution.” The combined datasets and sample collections from AL573 and AL594 strengthened international collaborations and multidisciplinary studies linking ecology, evolution, fisheries science, and biogeochemistry.

Bornholm Basin as focus area

The Bornholm Basin served as the primary focal region for both cruises, being the most important remaining spawning area for the Eastern Baltic cod population which is genetically separated from the more western Baltic cod stock. Additional sampling regions included the Western Baltic Sea (Kiel and Mecklenburg Bight, Arkona Basin), and the Gdańsk Deep, and the Stolpe Trench to the East. As a baseline, both expeditions conducted extensive hydrographic surveys measuring oxygen, salinity, and temperature, alongside detailed sampling of zooplankton and ichthyoplankton communities, including jellyfish, to assess the composition, abundance, and vertical and horizontal distribution of species. Zoo- and ichthyoplankton sampling in the Western Baltic (Mecklenburg Bight and Arkona Basin) contributed to spatially resolved recruitment data of Western Baltic cod,

which were integrated into the BMBF-DAM funded Project SpaCeParti and its “Winter cod 2021–2025” program.

Key collaborations and sampling programmes

The AL573 expedition in 2022 included several key international collaborations. These comprised artificial fertilization experiments with cod males and females from the Bornholm Basin to analyze key factors determining survival and condition (DTU Aqua, Copenhagen, Denmark, Dr. Sebastian Politis), sampling and experimentation on phytoplankton-virus and -grazer interactions (University of Hamburg, Dr. Luisa Listmann), and cod gonad and liver sampling for fecundity and parasite studies (DTU Aqua, Dr. Jonna Tomkiewicz). The AL594 expedition in 2023 continued and expanded these collaborations. It included ongoing work on phytoplankton-virus and -grazer interactions (University of Hamburg, Dr. Luisa Listmann), continued sampling of cod gonads and livers for fecundity and parasite studies (DTU Aqua, Dr. Jonna Tomkiewicz), and added a new component focusing on microbially mediated vitamin B1 (thiamine) dynamics in the Baltic Sea along a salinity gradient (GEOMAR, Dr. Kristin Bergauer). Across both expeditions, pelagic fisheries hauls and biological sampling targeted cod (*Gadus morhua*), sprat, whiting, and flatfish species. Subsamples were collected to determine stock structure, gonadal maturation, stomach contents, and egg production (for sprat and cod), and to obtain tissue and otolith samples for individual-level genomic and ecological analyses. These integrative datasets support ongoing investigations into stock recovery potential, reproductive success, and evolutionary responses under fishing pressure and environmental change.

Key findings on the status of the Baltic cod populations

Comparative results from the two cruises reveal both persistent and evolving patterns in the Eastern Baltic cod population. In 2022, cod nutritional condition was not significantly improving, and individual growth rates had declined over the previous 28 years. By 2023, the nutritional condition was no longer deteriorating, but growth rates continued to decrease, marking a 29-year downward trend (Han et al. 2025). In both years, the size distribution of the stock remained dominated by small individuals, with over 99% of cod measuring less than 50 cm in length, indicating that the stock has not yet recovered towards larger and more mature individuals. Genetic analyses from the 2022 expedition revealed a high diversity of mitochondrial (mt)DNA haplotypes, suggesting that the divergence between Western and Eastern Baltic cod is a relatively recent evolutionary event that only

happened after the last glacial maximum. The 2023 findings further indicate signs of fisheries-induced evolution, reflected in genomic changes associated with reduced growth rates, demonstrating ongoing adaptive responses to long-term exploitation pressures (Han et al. 2025).

Conclusion

Together, cruises AL573 (2022) and AL594 (2023) provide valuable continuity in the multi-decade monitoring of the Baltic Sea ecosystem in the context of the Baltic Sea Integrative Long-term Data Series (BILTS) at GEOMAR. The data generated underpin assessments of cod population health, recruitment dynamics, and eco-evolutionary processes in one of Europe's most environmentally stressed marine systems. These expeditions exemplify the integration of field ecology, evolutionary biology, and biogeochemistry within international research collaborations, contributing essential knowledge toward understanding and managing the changing Baltic Sea.

Reference

Han KY, Brennan RS, Monk CT, Jentoft S, Helmersen C, Dierking J, Hüsey K, Kokubun EE, Fuss J, Krause-Kyora B, Thomsen TB, Heredia BD & Reusch TBH, Genomic evidence for fisheries-induced evolution in Eastern Baltic cod, *Science Advances* 2025, 11 (26), Art.Nr.: eadr9889. DOI 10.1126/sciadv.adr9889.

Scientific Output

List of Publications

Han KY, Brennan RS, Monk CT, Jentoft S, Helmersen C, Dierking J, Hüsey K, Kokubun EE, Fuss J, Krause-Kyora B, Thomsen TB, Heredia BD & Reusch TBH, Genomic evidence for fisheries-induced evolution in Eastern Baltic cod, *Science Advances* 2025, 11 (26), Art.Nr.: eadr9889. DOI 10.1126/sciadv.adr9889.

Eglite E, Mohm C & Dierking J, Stable isotope analysis in food web research: Systematic review and a vision for the future for the Baltic Sea macro-region, *Ambio* 2023, 52, DOI 10.1007/s13280-022-01785-1.

Stoltenberg I, Mittermayer FH, Clemmesen C, Dierking J & Javidpour J, Predation on Baltic sea yolk-sac herring larvae (*Clupea harengus*) by the invasive ctenophore *Mnemiopsis leidyi*, *Fisheries Research* 2024, 273, 106973, DOI 10.1016/j.fishres.2024.106973.

Msc Theses

Endo Kokubun E, Eastern Baltic cod (*Gadus morhua*) mtDNA diversity through time (Masterarbeit), Christian-Albrechts-Universität zu Kiel, 2022, Kiel, Germany, 53 pp.

List of conference presentations

2025 | **Was würde Darwin zum heutigen Fischereimanagement sagen?**

Dialogforum Küstenfischerei, Grömitz, Germany

2025 | **Speciation under stress: Genomic and ecological divergence in Eastern**

Baltic Cod. Conference of the European Society for Evolutionary Biology ESEB, Barcelona, Spain

Data

Genetic data:

NCBI /Genbank; NCBI BioProject PRJNA1128530

Physical oceanography data:

Hinrichsen, Hans-Harald; Reusch, Thorsten B H; Dierking, Jan; Lehmann, Andreas (2025): Timeseries of physical oceanography in the Baltic Sea from 2011–2022

[dataset publication series]: PANGAEA

<https://doi.pangaea.de/10.1594/PANGAEA.979407>

AL573: Underway temperature and salinity data along the cruise track with a thermosalinograph (TSG) together with a SBE38 Thermometer: Pangaea

<https://doi.org/10.1594/PANGAEA.962710>

AL594: Underway temperature and salinity data along the cruise track with a thermosalinograph (TSG) together with a SBE38 Thermometer: Pangaea

<https://doi.org/10.1594/PANGAEA.962717>

Cruise Reports

AL573: <https://oceanrep.geomar.de/id/eprint/60207/>

AL594: <https://oceanrep.geomar.de/id/eprint/60748/>

AL575

Methane emissions at abandoned wells in the North Sea

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany
M. Haeckel, M. Schmidt

Objectives

The research of the AL575 cruise was conducted in the framework of the GEOSTOR project, which is part of the DAM mission “Marine Carbon Sinks in Decarbonization Pathways”. Methane gas emissions at abandoned wells have been investigated as an analogue for the assessment of the potential risk of leakage of CO₂ from subseafloor storage formations along boreholes drilled through the sedimentary overburden and barriers above those formations. Previous studies have documented that biogenic methane gas is emitted into the water column at many boreholes in the North Sea, particularly if drilled through or in the close vicinity of shallow gas accumulations in the uppermost 1000 m below the seafloor (Vielstädte et al., 2015 & 2017). One aim of this cruise was to enlarge the dataset of leaky wells in the UK sector of the North Sea and to test the statistical analyses of Böttner et al. (2020) that indicates a leakage propensity of more than 80%, if wells are drilled within a lateral distance of 300 m of a gas accumulation, and finally also to increase the overall number of measurements of drilling-induced gas leakage, i. e. the rate of leakage and its gas composition.

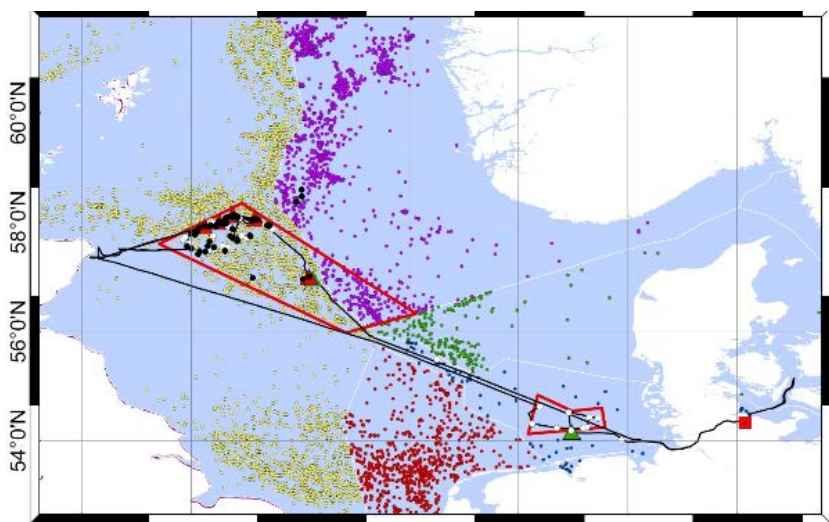


Figure 1: Map of the North Sea showing the locations of the more than 16,000 offshore wells (yellow: United Kingdom, pink: Norway, green: Denmark, blue: Germany, red: The Netherlands; white lines: EEZ borders). Hydroacoustically surveyed wells of AL575 and previous cruises are indicated by black (hydroacoustic flare) and white dots (no flare). Red triangles depict the locations of wells sampled for sediments, emitted gas, and water. The cruise track is shown as black line, harbour Kiel as red square, and the AL575 working areas are outlined in red.

Study Sites

During AL575, a total of 59 abandoned boreholes were examined for gas emissions by hydroacoustic surveys of the water column using the vessel's multibeam and singlebeam echosounders (Figure 1). The locations were selected based on the statistical analysis carried out by Böttner et al. (2020) in the UK sector of the North Sea, where the water depth is 80 to 150 m. At five sites, where gas flares were detected, the gas and sediments were sampled with the aid of ROV Phoca using high-pressure gas samplers and push cores, respectively. One of the stations was located above the top of a salt diapir structure.

Results

The analyses of the gas composition and methane isotopic signature confirmed our previous results from gas sampled at wells in the Norwegian sector of the North Sea that the gas emitted at the abandoned wells is of biogenic origin and not connected to the deeper conventional oil and gas reservoirs. In contrast, the gas being emitted above the salt diapir structure is of thermogenic origin, i. e. the salt tectonics created a gas migration pathway from the deep strata (> 3 km depth) to the seafloor. The gas leakage rates at the seafloor measured in situ at all seven sampled wells with the ROV HD cameras and a funnel so far vary

between 0.8 and 5.2 t of CH₄ per year. Including the work of AL575 a total of 120 wells have been examined hydroacoustically up to now in the British, Norwegian and German sectors of the North Sea, and gas emissions were identified at 59 wells. The hydroacoustic surveys conducted during AL575 could confirm the statistical analysis of Böttner et al. (2020) that showed that the risk of gas leakage decreases with the lateral distance of the well from a shallow gas accumulation: at a distance of less than 300 m, gas leakage is likely in over 80% of wells, while at a distance of more than 1000 m, the risk becomes low. Overall, in the UK study area, gas leakage is therefore likely to occur at about 50% of the boreholes. Applying this statistical result to the North Sea suggests that yearly about 4-42 kt of CH₄ could be emitted at the drilled wells. This would represent the dominant source of methane input into the North Sea and closes the gap in the North Sea methane budget (Vielstädte et al., 2017).

Based on the measured methane emission rates, the effective permeability in the rise path along the borehole was estimated to be several orders of magnitude higher than in the undisturbed background sediment layers (Jahnke, 2024). Compared to methane gas in natural gas accumulations, the CO₂ injected into subseafloor storage formations has a significantly higher specific density (about 20 times higher), a higher viscosity (about 5 times higher) and a much higher solubility in water (about 20 times higher). From this, a leakage rate of 10–50 t of CO₂ per year can be roughly estimated, depending on the overpressure created during the CO₂ injection. Due to the high solubility of CO₂ and the low rate of ascent, CO₂ stored at depths of approximately 2 km below the seafloor will probably only reach the seabed with a delay of a few decades.

Policy Work

Our scientific results have contributed to the new regulations of the European Commission on the reduction of methane emissions in the energy sector (<http://data.europa.eu/eli/reg/2024/1787/oj>), which were published in July 2024.

References

Böttner C, Haeckel M, Schmidt M, Berndt C, et al., Greenhouse gas emissions from marine decommissioned hydrocarbon wells: leakage detection, monitoring and mitigation strategies, *International Journal of Greenhouse Gas Control* 2020, 100, doi: 10.1016/j.ijggc.2020.103119.

Vielstädte L, Karstens J, Haeckel M, Schmidt M, et al., Quantification of methane emissions at abandoned gas wells in the Central North Sea, *Marine and Petroleum Geology* 2015, 68, doi:10.1016/j.marpetgeo.2015.07.030.

Vielstädte L, Haeckel M, Karstens J, Linke P, et al., Shallow gas migration along hydrocarbon wells – An unconsidered, anthropogenic source of biogenic methane in the North Sea, Environmental Science & Technology 2017, 51, doi:10.1021/acs.est.7b02732.

Scientific Output

List of Publications

Jahnke A, Gasleckagen an Altbohrungen in der Nordsee, Bachelor thesis, CAU Kiel, 2024, 58 p.

Kraemer D, Schmidt K, Klimpel F, Rauch U, et al., Tracking the distribution of persistent and mobile wastewater-derived substances in the southern and central North Sea using anthropogenic gadolinium from MRI contrast agents as a far-field tracer, Marine Pollution Bulletin 2024, 207, doi:10.1016/j.marpolbul.2024.116794.

List of conference presentations

2025 | **Greenhouse gas emissions from marine decommissioned hydrocarbon wells: leakage detection, monitoring, and mitigation strategies** Annual Meeting WELLFATE project, Oslo, Norway.

2024 | **Greenhouse gas emissions from marine decommissioned hydrocarbon wells: leakage detection, monitoring and mitigation strategies** SODIR Workshop, Stavanger, Norway.

Data

Subbottom profiler:
<https://doi.pangaea.de/10.1594/PANGAEA.977814>

Singlebeam echosounder:
<https://doi.pangaea.de/10.1594/PANGAEA.977813>

Multibeam echosounder:
data submitted to Pangaea in April 2025

Ship underway data:

<https://doi.pangaea.de/10.1594/PANGAEA.974224>

water column CH₄ concentrations:

<https://doi.pangaea.de/10.1594/PANGAEA.979903>

Water rosette CTD sensors:

<https://doi.pangaea.de/10.1594/PANGAEA.984201>

Atmospheric Picarro CH₄ + CO₂ concentrations:

<https://doi.pangaea.de/10.1594/PANGAEA.982665>

<https://doi.pangaea.de/10.1594/PANGAEA.983846>

<https://doi.pangaea.de/10.1594/PANGAEA.983855>

<https://doi.pangaea.de/10.1594/PANGAEA.983931>

<https://doi.pangaea.de/10.1594/PANGAEA.983847>

<https://doi.pangaea.de/10.1594/PANGAEA.983856>

<https://doi.pangaea.de/10.1594/PANGAEA.983854>

<https://doi.pangaea.de/10.1594/PANGAEA.983850>

<https://doi.pangaea.de/10.1594/PANGAEA.983849>

<https://doi.pangaea.de/10.1594/PANGAEA.983852>

<https://doi.pangaea.de/10.1594/PANGAEA.983848>

<https://doi.pangaea.de/10.1594/PANGAEA.983857>

<https://doi.pangaea.de/10.1594/PANGAEA.983853>

<https://doi.pangaea.de/10.1594/PANGAEA.983851>

<https://doi.pangaea.de/10.1594/PANGAEA.982666>

Weather data:

<https://doi.pangaea.de/10.1594/PANGAEA.983868>

<https://doi.pangaea.de/10.1594/PANGAEA.983864>

<https://doi.pangaea.de/10.1594/PANGAEA.983860>

<https://doi.pangaea.de/10.1594/PANGAEA.983932>

<https://doi.pangaea.de/10.1594/PANGAEA.983866>

<https://doi.pangaea.de/10.1594/PANGAEA.983833>

<https://doi.pangaea.de/10.1594/PANGAEA.983829>

<https://doi.pangaea.de/10.1594/PANGAEA.983859>

<https://doi.pangaea.de/10.1594/PANGAEA.983869>

<https://doi.pangaea.de/10.1594/PANGAEA.983858>

<https://doi.pangaea.de/10.1594/PANGAEA.983867>

<https://doi.pangaea.de/10.1594/PANGAEA.983865>

<https://doi.pangaea.de/10.1594/PANGAEA.983862>

<https://doi.pangaea.de/10.1594/PANGAEA.983863>

<https://doi.pangaea.de/10.1594/PANGAEA.983861>

Cruise Report

AL575: https://doi.org/10.3289/cr_al575

AL586 and AL596

North Sea Plastics I & II: Fate and impact of river-borne microplastics and their chemical additives in the North Sea

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany
A. Beck, A. Engel, E. Achterberg

Overview

The river source of plastic debris to the southern North Sea region appears to be increasing over the past several decades, with a strong seasonal control on riverine MP transport and discharge. The paired cruises AL586 and AL596 were conducted to link plastic pollution in the North Sea to seasonal studies in the Elbe and Thames rivers as part of the H2020 LABPLAS project, with the objective to understand the transport and fate of river-derived small micro- and nanoplastics (SMNPs) in the North Sea. The specific objectives of the North Sea Plastics I & II cruises form a framework for mapping the distribution of microplastics and their associated chemical contaminants in the coastal southern North Sea and assessing spatial and temporal variation in the delivery and fate of these land-derived pollutants.

Background

The distribution of microplastic debris in European coastal waters is heterogeneous (e. g., Maes et al., 2018), but there are clear hotspots at river mouths (Galgani et al., 2000). The putative river source of most plastic debris in this region appears to be increasing over the past several decades (Maes et al., 2018), and microplastic concentrations vary with discharge (Mani et al., 2020), suggesting a strong seasonal control on MP transport and distribution in the receiving coastal sea. The North Sea Plastics cruises link plastic pollution in the North Sea to seasonal studies in the Elbe and Thames Rivers as part of the LABPLAS project, with the objective to understand the transport and fate of river-derived SMNPs in the North Sea. The North Sea

Plastics I & II cruises revisited a number of stations sampled during the AL534/2 cruise in March 2020 (AL534/2 Stations 8, 10, 12, and 14). The work in the North Sea Plastics I & II cruises is mostly very similar to the methods used in the previous cruise, and the data provide a perspective on microplastic pollution over a longer time period.

There is clear spatial variation in the types of MP in North Sea German coastal waters, with urban and industrial signatures dominating near the Elbe estuary (Dibke et al., 2021). However, water treatment plants discharging into the North Sea appear to more efficiently remove MPs compared with those in the Black and Mediterranean Sea regions (Siegfried et al., 2017). Concentrations of MP in the Thames estuary are some of the highest recorded globally (Rowley et al., 2020), although modeling suggests that much of the MP load in the river is deposited in sediments (Whitehead et al., 2021).

External inputs of litter to the North Sea are likely dominated by the two main river systems in the region, the Thames and Elbe. Both rivers show marked seasonality with highest flow in March and April and lowest flow from August to September (Wilson et al., 2013; Bartl et al., 2009). The Elbe river is highly industrialized, including Germany's second largest city, Hamburg, and its metro region (population > 7 million) with the major wastewater treatment plant "Köhlbrandhöft" treating sewage water of some 2.4 M people. The Thames river basin supports large urban and industrialized areas, such as the city of London in the East Thames area, but also rural areas in the west Thames area. The river receives treated sewage effluent from a population > 13 million, which makes it one of the largest anthropogenic-riverine inputs to the North Sea.

Methods

Cruise AL586 sampled four primary and two intermediate stations between the Elbe and Thames river estuaries, and Cruise AL596 sampled five primary and five intermediate stations (Figure 1). Primary stations included CTD casts to collect discrete water samples between surface and seafloor, "snow catcher" sampling to collect settling aggregates, sediment sampling with Van Veen grab, suspended particle and plankton sampling using a vertical WP2 net, surface neusten sampling using a catamaran trawl, and sea surface microlayer sampling by Garrett screen. Intermediate stations were sampled only by catamaran net. Additional sampling along the cruise track included surface water sample collection from the ship's underway seawater supply, and during calm weather, floating litter surveys to count the abundance of floating debris.

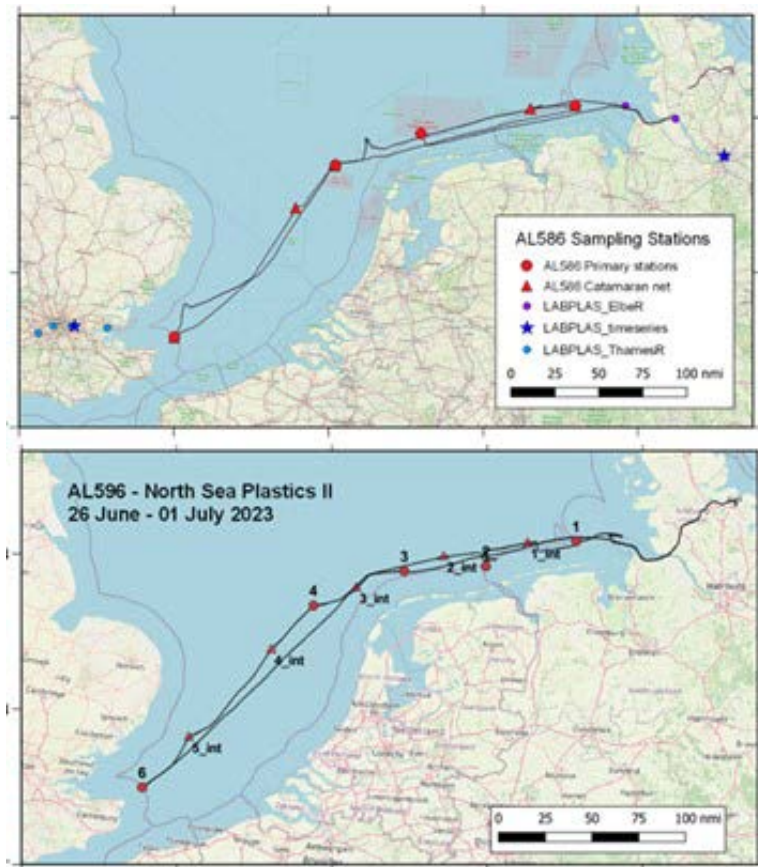


Figure 1: Cruise tracks and stations sampled during AL586 (upper panel) and AL596 (lower panel). Note that the stations 6 to 1 in Figure 1 correspond to stations 7 to 12 in Figure 2.

Selected Results

Plastic concentrations were analyzed in every station for all the samplings carried out during the two years. The average abundance of plastics debris over the entire study area was $3.09 \text{ plastics m}^{-3}$. The number of plastics in the stations varied along the three aquatic systems with the highest concentration found in Thames River (St.6, $114.8 \text{ plastics m}^{-3}$) and the lowest average being $0 \text{ plastics m}^{-3}$ at station 11 in the North Sea. The river estuaries generally had the highest concentration of plastics, consistent with the trapping effect exerted by estuarine physical processes. This is also likely a major control on the export of plastics to the North Sea, and one reason why the concentrations there are much lower than in the rivers.

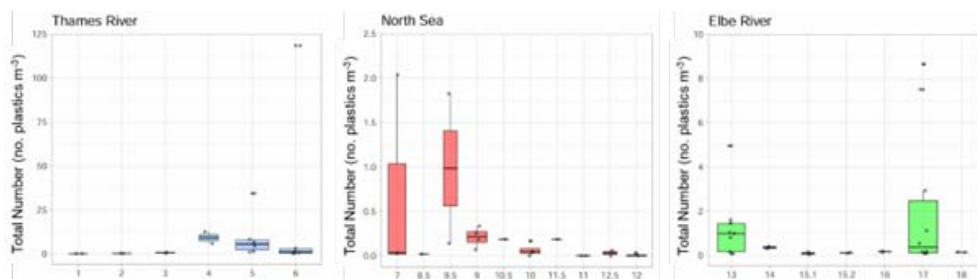


Figure 2: Total floating plastic concentrations (micro, meso and macro) in the three aquatic systems. Thames River is in blue (left), North Sea in red (middle) and Elbe River in green (right). The stations are plotted in longitudinal order from west to east. Note the difference y-axis scales. (From Rodríguez-Torres et al., 2025).

Plastic additive chemicals

An analysis method with 84 plastic additive chemicals was applied, of which only 18 target compounds were measurable in the field samples. Most of the target compounds were detected at levels between 0.1 and a few ng/L (Figure 3). The PFAS class of compounds was most frequently detected, and four PFAS were found in every sample (NfBSA, PFHpA, PFOA, PFOS). PFAS concentrations were markedly higher toward the Elbe estuary. The antioxidant DPA was found during both seasons in the central or eastern region, but only in deep water. Plasticizers were the most infrequently detected compounds, found in only 5–14% of the samples. In contrast to the distribution of plastic litter, additive concentrations were higher toward the eastern side of the sampling region, near the Elbe estuary. These are the first such data for plastic-related chemicals in the North Sea, and will allow ecological risk assessment for plastic pollution that is separate from the more widely-recognized effect of plastic particles.

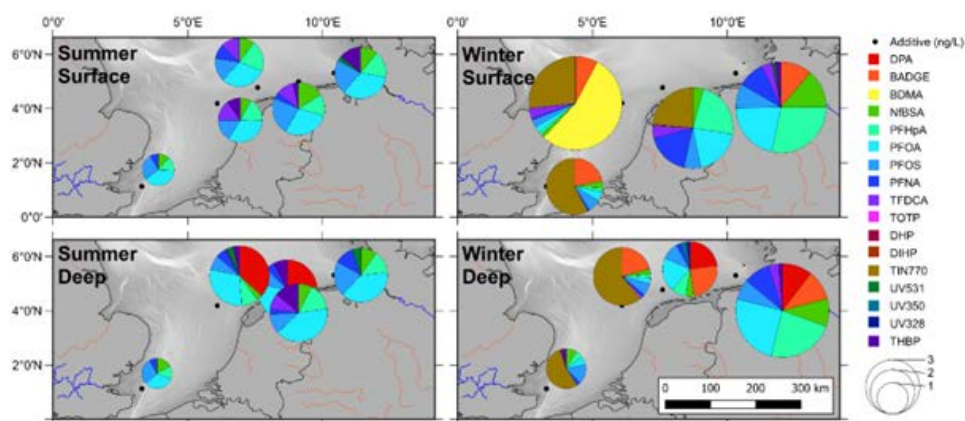


Figure 3: Spatial distribution of detected additives in surface (upper panels) and deep water (lower panels) in summer (AL596; left) and winter (AL586; right) seasons.

References

Bartl S, Schümborg S & Deutsch M, Revising time series of the Elbe river discharge for flood frequency determination at gauge Dresden, *Natural Hazards and Earth System Sciences* 2009, 9(6), 1805–1814.

Dibke C, Fischer M & Scholz-Böttcher BM, Microplastic mass concentrations and distribution in German bight waters by pyrolysis–gas chromatography–mass spectrometry/thermochemolysis reveal potential impact of marine coatings: do ships leave skid marks?, *Environmental Science & Technology* 2021, 55(4), 2285–2295.

Galgani F, Leaute JP, Moguedet P, Souplet A, Verin Y, Carpentier A, Goraguer H, Latrouite D, Andral B, Cadiou Y, Mahe JC, Poulard JC, Nerisson P, Litter on the sea floor along European coasts, *Marine pollution bulletin* 2000, 40(6), 516–527.

Maes T, Van der Meulen MD, Devriese LI, Leslie HA, Huvet A, Frère L, Robbens J & Vethaak AD, Microplastics baseline surveys at the water surface and in sediments of the North-East Atlantic, *Frontiers in Marine Science* 2017, 4, 135.

Mani T & Burkhardt-Holm P, Seasonal microplastics variation in nival and pluvial stretches of the Rhine River–From the Swiss catchment towards the North Sea, *Science of the Total Environment* 2020, 707, 135579.

Rowley KH, Cucknell AC, Smith BD, Clark PF & Morritt D, London's river of plastic: High levels of microplastics in the Thames water column, *Science of the Total Environment* 2020, 740, 140018.

Siegfried M, Koelmans AA, Besseling E & Kroeze C, Export of microplastics from land to sea. A modelling approach, *Water research* 2017, 127, 249–257.

Whitehead PG, Bussi G, Hughes JM, Castro-Castellon AT, Norling MD, Jeffers ES, Rampley CPN, Read DS & Horton AA, Modelling microplastics in the river thames: sources, sinks and policy implications, *Water* 2021, 13(6), 861.

Wilson D, Hannah DM & McGregor GR, A large-scale hydroclimatological perspective on western European river flow regimes, *Hydrology Research* 2013, 44(5), 809–833.

Scientific Output

List of Publications

Ehlebracht PM, Geographical distribution of microplastics in the southern North Sea: A holistic approach emphasising annual and seasonal variations, BS Thesis 2024, University of Hamburg.

Hewett S, Microplastic distribution in fish in the North Sea and River Medway, MS Thesis, National Oceanography Centre (NOC) 2024, University of Southampton.

Rodríguez-Torres R, Beck A, Stock F, Pabortsava K, Lombard F, Labis E, Caray-Counil EL, Lampitt R, Horton A, Hoehn DP, Farcas A, Aldridge J, Graham J, Bakir A, McEwan R & Pedrotti ML, Spatial distribution and characterization of plastic pollution in a continuous environment combining in situ observations with 3D litter tracer model: Thames River, North Sea and Elbe River, Water Research 2025, submitted for publication.

Rysiecki A, Microplastic ingestion by fish of the River Elbe (Germany) and the North Sea, MS Thesis, National Oceanography Centre (NOC) 2023, University of Southampton.

Shettigar NA, Numerical modelling of plastic dispersal in aquatic environments, PhD dissertation 2025, KU Leuven.

Data

Continuous thermosalinograph data (AL586):
<https://doi.org/10.1594/PANGAEA.965689>

Continuous thermosalinographa data(AL596):
<https://doi.pangaea.de/10.1594/PANGAEA.965683>

Cruise Reports

AL586: https://doi.org/10.3289/CR_AL586

AL596: https://doi.org/10.3289/CR_AL596

AL595

New Insights into the Grimsey Hydrothermal Field Offshore Iceland

Authors

GEOMAR Helmholtz Centre for Ocean Research | Kiel, Germany

S. Hölz, M. Perner, N. Adam-Beyer, D. Tasdemir, A. Krätschell, S. Petersen, S. Sander

Helmholtz Centre for Geosciences Potsdam | Potsdam, Germany

J. Stammeier

University Hamburg | Hamburg, Germany

L. Verheyen, S. Brix

In the years 2018 and 2019, the Electromagnetic (EM) working group at GEOMAR carried out two cruises onboard RV Poseidon (POS524, POS535) to carry out EM experiments at the Grimsey Hydrothermal Field (GHF), which is part of the Tjörnes Fracture Zone to the North of Iceland. Aim of these past cruises was to study the effects of hydrothermal activity and potential mineralizations onto the electrical conductivity. First interpretations of EM data revealed an extended good conductor starting at a depth of about 15–20m beneath the seafloor to the West of the active site, which could in theory be explained by saline, boiling fluids. However, temperature measurements and core sampling above this EM anomaly hardly give any evidence of hydrothermal activity and do not support the presence of substantial amounts of boiling fluids at relatively shallow depths. Instead, it seems likely that the EM anomaly is – at least in parts – connected to the presence of massive mineralizations in the subsurface.

To gain further insight into the GHF system, we proposed to perform pending system tests with GEOMAR's new Hover-AUVs (ANTON & LUISE) at the GHF. The system tests were approved and carried out during cruise AL595 onboard RV Alkor (31.05.–20.06.2023). The collection of high-resolution bathymetry (AUV ANTON) and photogrammetry (AUV LUISE) were accompanied by microbial investigations utilizing gravity and multi-coring (MUC) in combination with deployments of the BIGO lander system. MUC samples and additional water samples collected with the CTD were also used in the scope of marine natural product research. Microbial

and natural product research were carried out as part of the Topic 8 InnoPool project “High CO₂ – metabolic responses and bioeconomic opportunities” (01.2022–12.2024). Finally, pore water samples collected from the gravity cores were analyzed for pore water geochemistry to complete investigations already carried out during the previously mentioned cruises with RV Poseidon. Due to the long transit from Kiel to the working area and back (Figure 1) – 11 days in total – we had a total of nine working days to carry out tests and collect samples.

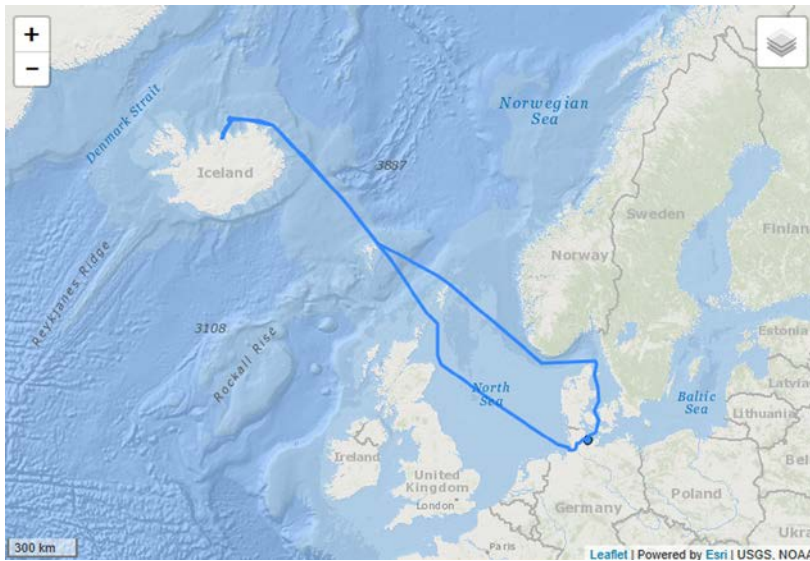


Figure 1: Ship track of RV Alkor for cruise AL595 from Kiel to the working area of the Grimsey Hydrothermal Field to the North of Iceland.

For the collection of bathymetric data, AUV ANTON was equipped with a Norbit Wideband Multibeam Sonar WBMS with an operating frequency of 400kHz, gain settings of 20 first and 40 for subsequent dives, a swath coverage of 130°, and an automatic ranging mode. The distance to the ground was set to 20m, which ensured a stable DVL lock onto the seafloor. Profile lines were carried out with a spacing of 50m at a speed of 0.5m/s. Post cruise, the acquired data were processed (outlier rejection, tide correction, ...) using the Qimera QPS software package to create a combined grid from data collected in five dives with a final resolution of 0.5m (Figure 2). A shaded relief image of the grid shows the hydrothermal mounds in the eastern part of the grid in unprecedented detail. A prominent feature in the western part of the relief shows an N-S striking elongated, smooth ridge. We interpret this feature as a drumlin, which would indicate that the larger structure and potentially old generations of the hydrothermal field were influenced by glaciers in ground contact with the seafloor during the last glaciation. Even though thermodynamic modeling (Geirsdottir et al., 2019) and striations on the island of Grimsey about 20km to the West of GHF

(Einarsson, 1967) indicate that the maximum extent of the Icelandic ice-sheet might have reached the GHF during the last glaciation, we can find no mentioning of a potential glacial influence onto the GHF in any of the almost 100 articles directly dealing with the hydrothermal field.

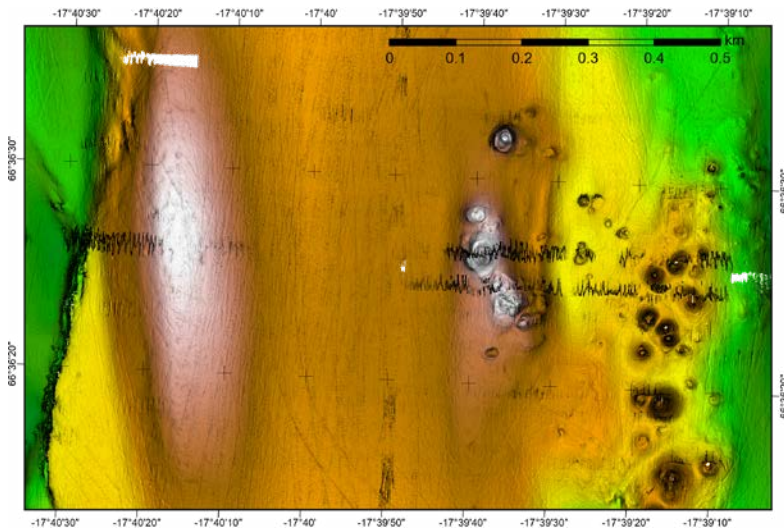


Figure 2: Final grid (resolution 0.5m) of bathymetric data collected at the GHF during cruise AL595.

AUV Luise was equipped with a CoraMo mk II camera and eight high power LEDs to take pictures for photogrammetric surveys over five selected targets. An altitude of 2.6m was determined to be optimal in terms of allowing for a safe operation while still producing well illuminated images. Due to the shallow altitude operation, it was not deemed safe to operate the AUV close to the rather steep mound structures of the hydrothermal field. Instead, five targets of interest were chosen in more suitable, rather flat terrain to produce photo mosaics with sizes of 35m x 35m, each. Figure 3 shows a zoom into one of the mosaics and demonstrates the achievable image quality, which easily allows for the detection and identification of objects on a sub-centimeter scale. This allows for the study of megafaunal communities and biodiversity patterns, e. g. by J.L. Verheyen (2024) who found that the GHF with its high-temperature venting and anhydrite chimneys lacks endemic species and that communities rely on substrate diversity and opportunistic taxa that exploit hydrothermal environments. The acquired mosaics will be used as part of a PhD-proposal at the University Hamburg to further study the megafauna of vent sites around Iceland (Verheyen, to be submitted).

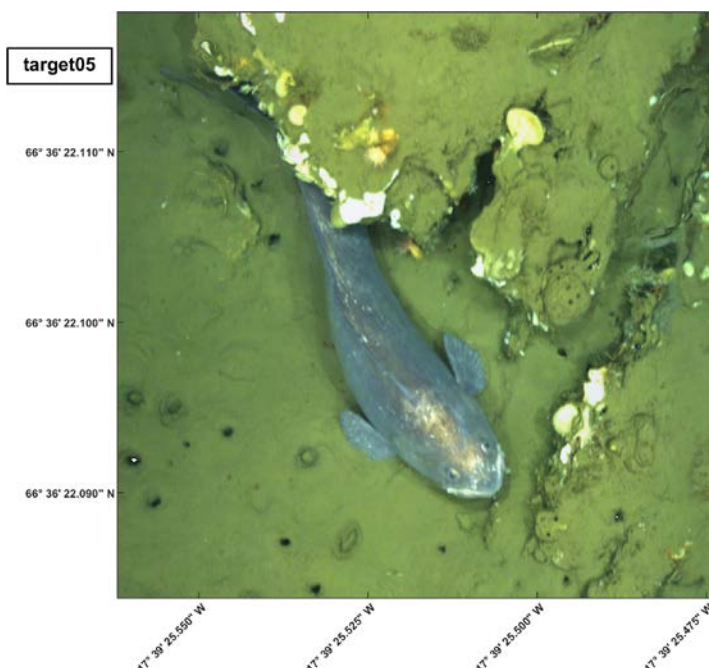


Figure 3: Zoom into a photo mosaic taken during the last mission with AUV Luise. The picture covers an area of about 0.8m x 0.8m.

Geochemical analyses of pore fluids were carried out at GFZ Potsdam and were integrated into the database build from analyses of samples collected during the previous cruises POS524 and POS535. High Cu-values ($> 1.000 \mu\text{g/l}$) in combination with elevated Zinc values ($> 100 \mu\text{g/l}$) were frequently observed in pore fluids not only at or close to active sites, but also at a distal site close to the drumlin shaped feature. High values are often observed in confined layers, which seems to indicate that the transport of minerals from depth comes in pulses and is not constrained to the active venting area.

Investigations into the microbial communities were especially driven by the interest to find out how they would react to an environment with extremely high CO_2 levels ($>10\%$). For the analyses of marine natural products, 54 MUC samples and seven samples from CTD and BIGO were taken from different layers and placed on different media (Marine Agar, Tryptic soy broth, Wickerham, Potato-Dextrose-Agar) for the enrichment of bacteria and fungi, of which 195 and 13, respectively, were identified. After cultivation of selected strains, one extract (*Streptomyces* sp.) showed high bioactivity in relevant tests (ESCAPE panel, two human pathogenic yeasts, two fish pathogenic bacteria). Further testing (universal siderophore CAS assay, CAS assay with isolates from all stations and untargeted metabolomics of promising strains) are work in progress.

References

Geirsdóttir A, Miller GH, Axford Y & Ólafsdóttir S, Holocene and latest Pleistocene climate and glacier fluctuations in Iceland, Quaternary Science Reviews 2009, 28, 2107–2118.

Einarsson T, Zu der Ausdehnung der weichselzeitlichen Vereisung Nordislands. Sonderveröffentlichung des Geologischen Instituts Universität Köln, 1967, vol. 13, pp 167–173.

Scientific Output

List of Publications

Adam-Beyer N, Hölz S, Wallmann K, Henkel S, Sommer S & Perner M, In situ experiments reveal distinct biogeochemical cycling and associated benthic microbial communities in the Grimsey hydrothermal vent field (in preparation).

Verheyen JL, Brix S, Burgos J, Hölz S, Lörz A, de Montety L, Olafsdottir SH, Ragnarsson S & Gollner S, Habitat heterogeneity and faunal assemblages at Kolbeinsey and Grimsey hydrothermal vent fields of northern Iceland (in preparation for Biogeosciences).

Verheyen JL, Biodiversity and Community Patterns in Shallow-Water Hydrothermal Vents: A Comparative Study of Kolbeinsey and Grimsey, Iceland, Master thesis, 2024, University of Hamburg, 67 pp.

List of conference presentations

2023 | **New Insights into the Development of the Grimsey Hydrothermal Field.**
EMTF Meeting, St. Marienthal, Germany

Data

<https://marine-data.de/expeditions/AL595>
(ship track & events; further data to be published in October 2026, see cruise proposal & cruise report).

Cruise Report

AL595: https://doi.org/10.3289/CR_AL595

AL597

Biogeo-optical and -chemical characterization of cyanobacterial blooms in the Baltic Sea for ocean colour satellite remote sensing

Authors

Helmholtz Centre Hereon | Geesthacht, Germany

M. Hieronymi, R. Röttgers, D. Behr, S. Bi, K., Heymann, M. Novak, Y.G. Voynova

University of Tartu, Tartu Observatory | Tartu, Estonia

K. Alikas, I. Ansko, I.-A. Rahn

Stockholm University | Stockholm, Sweden

S. Kratzer, S. Pramlall

University of Oldenburg | Oldenburg, Germany

C. Thölen

University of Nantes | Nantes, France

P. Roux

Ocean Colour satellite remote sensing enables continuous and global monitoring of phytoplankton biomass and other water constituents in the upper layer of the ocean as well as of coastal and inland waters. The Baltic Sea is a particularly difficult water body to interpret from a remote sensing perspective; compared to other sea areas, it is very dark due to the high concentration of coloured dissolved organic matter brought in by many rivers and due to the limited water exchange with the North Sea. It also has intense cyanobacterial blooms in the summer months, which is not usual for temperate seas. This leads to large uncertainties in satellite products and limited usability of observational data. The measurement of specific optical properties in the field, especially of cyanobacteria, and the determination of biogeochemical properties are essential for the evaluation and further development of satellite products, e. g., regarding phytoplankton diversity or the marine carbon cycle.

During the RV Alkor cruise AL597, relevant bio-geo-optical and -chemical parameters were determined in the upper water layer and at the sea surface. High concentrations of cyanobacteria were detected and sampled. The cruising area was optimised for match-ups especially with Copernicus satellites (i. e., Sentinel-3 OLCI and Sentinel-2 MSI), but also with the German hyperspectral EnMAP mission (see Figure 1), which resulted in an exceptionally large number of inter-comparison measurements for validation. The medium-term goal of this research is the development of novel Earth observation products to quantify biodiversity, detect environmental risks and better characterise the carbon cycle in the ocean.

One of the core results related to this research expedition is a dataset of Sentinel-3 OLCI satellite observations of the entire North Sea and Baltic Sea region for June to September 2023, which includes a novel data processing scheme and provides many links to the field measurements [Hieronymi et al., 2025]. The primary parameter for water quality retrievals is spectral remote-sensing reflectance, which was measured and compared on board in different ways, including with a novel community processor [Tilstone et al., 2025]. This reflectance is used to derive inherent optical properties (IOPs) of water constituents and, from this, the concentrations of the water constituents such as total chlorophyll-a (Chl) or particulate organic carbon (POC). Our POC measurements during AL597 in the Baltic Proper were between 0.25 and 0.86 g m⁻³ and in the Gulf of Finland between 0.54 and 0.96 g m⁻³ [Novak and Röttgers, under review]; these values are in the same order of magnitude as estimated from the satellite data (see Figure 2), but actual validation of all parameters is still pending. For comparison, POC measurements in the North Sea show usually lower values of 0.05 to 0.5 g m⁻³; but in the turbid parts of the German Bight and in the Elbe estuary, POC values up to 15 g m⁻³ have been measured (Röttgers et al., 2023). Several articles are in progress that deal with comparisons of in situ measurements of diverse parameters and their satellite estimates.

Another focus of ongoing research is the water-type-specific analysis of water samples, especially their absorption and scattering properties. Essentially all spectral IOPs were measured precisely with state-of-the-art methods with the aim of improving our theoretical understanding of bio-geo-optical modelling (Bi et al., 2023). Another objective was also to compare different measurement systems and analysis protocols, but also the variation of results with the same devices from different groups. Water turbidity, for example, was measured with three portable devices made by HACH (USA). Another focus of the investigations was on describing the phytoplankton community using imaging techniques, fluorescence properties, and pigment distributions.

Regarding comparisons between sea-going measurements and satellite data, it should be noted that reference data should be evaluated in context of similar biogeochemical properties of waters to assess the suitability of satellite

algorithms, for example. In fact, the sampled water masses during the Baltic Sea cruise were very similar and optically dominated by high concentrations of colored dissolved organic matter (CDOM); in the optical water type (OWT) classification by Bi and Hieronymi [2024], which distinguishes ten water types, only one class was populated with maximum memberships (OWT 4a). The measurement data obtained is very valuable, but further extensive expeditions in other sea areas are necessary for comprehensive satellite validation. However, a spatial analysis of the satellite data also shows that the measurement data is representative for major parts of the Baltic Sea [Hieronymi et al., 2025].

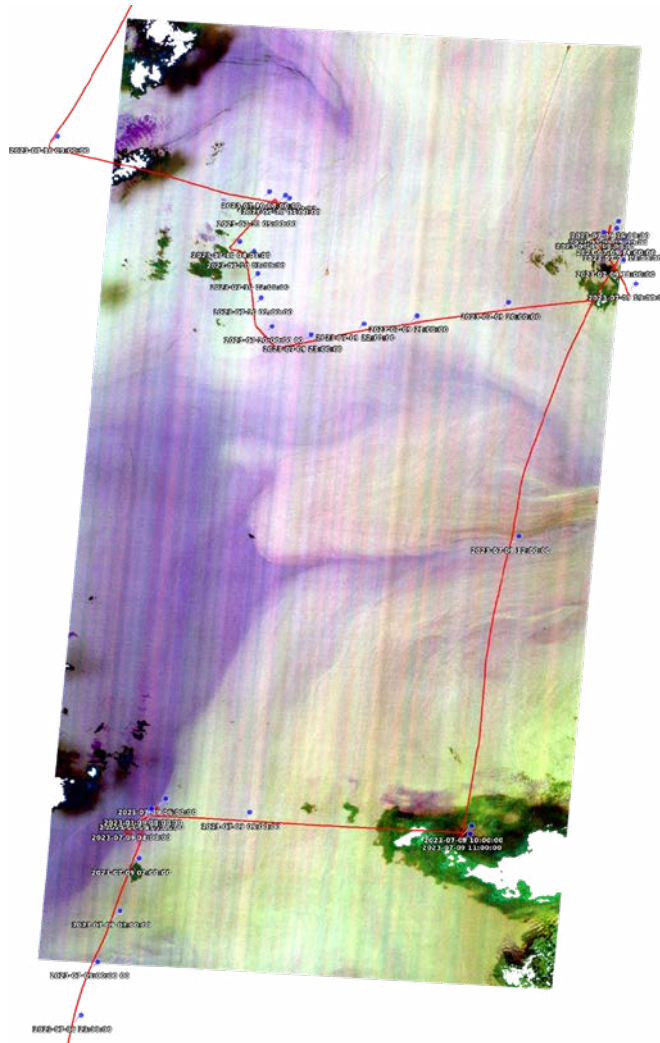


Figure 1: Cruise track on July 9, 2023 (with stations 8 to 10 southeast of the island of Gotland) optimized for comparison with satellite data, here with an RGB image from the German EnMAP mission (after atmospheric correction, image swath 30 km).

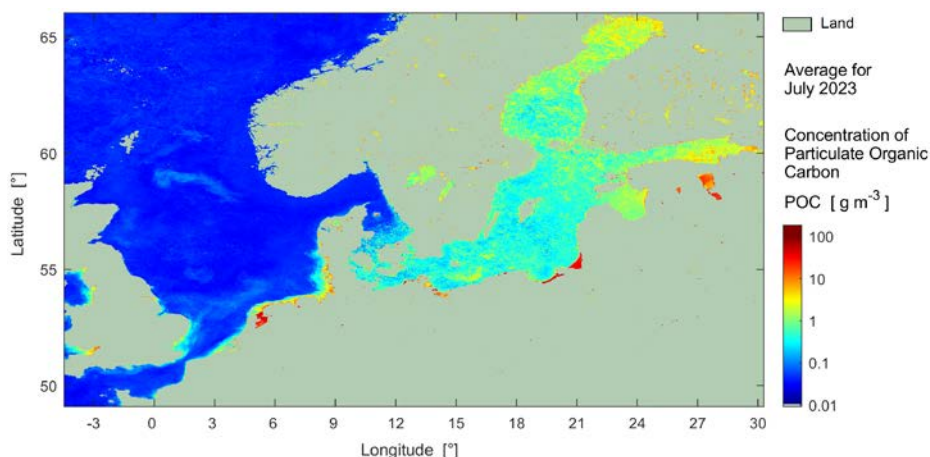


Figure 2: Satellite-based estimate of the concentration of particulate organic carbon in the upper water column for July 2023, during the RV Alkor AL597 cruise in the Baltic Sea [from Hieronymi et al., 2025] (contains modified Copernicus Sentinel-3 OLCI data [2023]).

References

- Bi S & Hieronymi M, Holistic optical water type classification for ocean, coastal, and inland waters, *Limnology and Oceanography* 2024, 69(7), 1547-1561, doi: 10.1002/lno.12606.
- Bi S, Hieronymi M & Röttgers R, Bio-geo-optical modelling of natural waters. *Frontiers in Marine Science* 2023, 10, 1196352, doi: 10.3389/fmars.2023.1196352.
- Röttgers R, Bi S, Burmester H, Heymann K, Hieronymi M, Krasemann H & Schöfeld W, Water inherent optical properties and concentrations of water constituents from the German Bight and adjacent regions: spectral data of the phytoplankton light absorption coefficient [dataset], PANGAEA 2023, doi: 10.1594/PANGAEA.954981.
- Tilstone GH, Jordan TM, Aurin D, Białek A, Deru A, Ramsay A, Hieronymi M, Dall'Olmo G, Ligi M, Kovach C, Ansko I, Ondrusek M, Vabson V, Zibordi G, Gossn JI, Kwiatkowska E & Vendt R, Radiometric field inter-comparison of fiducial reference measurements using an open source community processor, *Optics Express* 2025, 33(7), 15756-15781, doi: 10.1364/OE.551042.

Scientific Output

List of Publications

Hieronymi M, Bi S & Behr D, Sentinel-3 OLCI daily averaged earth observation data of water constituents (Version 2), World Data Center for Climate (WDCC) at DKRZ 2025, doi: 10.26050/WDCC/AquaINFRA_Sentinel3_v2.

Hieronymi M, Behr D, Bi S & Röttgers R, Optical complexity of North Sea, Baltic Sea, and adjacent coastal and inland waters derived from satellite data, Earth Syst. Sci. Data Discuss. [preprint], doi: 10.5194/essd-2025-443, in review, 2025.

Novak MG & Röttgers R, Spectral variability in particulate light backscattering in the sea: Resolving fine-scale optical features and their biogeochemical significance, Opt. Express, under review (submitted 19/09/2025).

List of conference presentations

2025 | **Sentinel-3 OLCI observation-based digital twin component for aquatic carbon in the land-sea continuum**, Living Planet Symposium 2025, Vienna, Austria

2025 | **EO based estimates of water transparency to support the monitoring and reporting under EU directives**, Living Planet Symposium 2025, Vienna, Austria

2025 | **Aquatic Remote Sensing Research**, 2nd FRM4SOC Workshop on Calibration and Characterisation of Ocean Colour Field Radiometers, Tartu, Estonia

2025 | **Water remote sensing with EnMAP – Hyperspectral features for various optical water types**, 2nd EnMAP User Workshop 2025, Munich, Germany

2025 | **The beauty of clear skies at sea – About challenges with clouds and the atmosphere in Ocean Colour satellite remote sensing**, Leipziger Meteorologisches Kolloquium, Leipzig, Germany

2024 | **Spectral measurements of particulate volume scattering at a backward angle of natural waters from the North and Baltic Sea**, Ocean Optics XXVI, Las Palmas, Gran Canaria, Spain

2024 | Evolution of the Sentinel-3 OLCI Neural Network Swarm processing chain for inland, coastal and ocean waters, Ocean Optics XXVI, Las Palmas, Gran Canaria, Spain

2024 | Consistency of above-water TriOS RAMSES measurements with Sentinel 3 OLCI products over the Baltic Sea, Ocean Optics XXVI, Las Palmas, Gran Canaria, Spain

2023 | Validation of Sentinel-3 OLCI standard products and alternative approaches over absorbing and eutrophic inland and coastal waters, 8th S3VT meeting, Darmstadt, Germany

2023 | Evolution of the novel OLCI Atmospheric Correction for Diverse Optical Water Types A40, 8th S3VT meeting, Darmstadt, Germany

List of theses

Novak, MG, PhD, University of Oldenburg (2026)

Rahn, I-A, PhD, University of Tartu (ongoing)

Thölen, C, PhD, University of Oldenburg (ongoing)

Data

Cruise summary report inventory:
<https://csr.seadatanet.org/report/21031722>

Copernicus Sentinel-3 OLCI satellite data related to cruise:
https://doi.org/10.26050/WDCC/AquaINFRA_Sentinel3_v2

Cruise Report

AL597: https://doi.org/10.3289/CR_AL597

AL611

The role of subglacial landforms for offshore freshened groundwater below the southeastern North Sea

Authors

Institute of Geosciences, Kiel University | Kiel, Germany

A. Lohrberg, N. Moosdorf, H. Grob, E. Hadré, S. Krastel

University of Hawai'i at Manoa | Honolulu, USA

A. Haroon

Leibniz Centre for Tropical Marine Research | Bremen, Germany

N. Moosdorf

Introduction

Offshore freshened groundwater (OFG) constitutes an underexplored component of the global hydrological cycle that has increasing significance for coastal water resources and subsurface processes. Reservoirs of OFG have been documented beneath continental shelves worldwide (Post et al., 2013; Micallef et al., 2021), yet their origin, spatial extent, and long-term stability remain uncertain. Freshwater emplacement beneath marine shelves has been attributed, among other processes, to meteoric recharge during lowstands and to infiltration of subglacial meltwater during glaciations (Meisler et al., 1984; Person et al., 2003; Cohen et al., 2010; Siegel et al., 2014). Constraining the relative importance of these mechanisms is essential for evaluating the volume and preservation of offshore groundwater resources.

The North Sea is a key region for testing these processes because its subsurface preserves extensive networks of tunnel valleys and other landforms carved by pressurised meltwater beneath the Fennoscandian and British–Irish ice sheets (Clark et al., 2018; Huuse & Lykke-Andersen, 2000; Lohrberg et al., 2020, 2022; Ottesen et al., 2020). These valleys penetrate deeply into Neogene and Paleogene sequences that also host major aquifers onshore (Sandersen & Jørgensen, 2003). Their geometry and distribution suggest that they once acted as hydraulic

conduits below ice sheets interacting with aquifer systems (Piotrowski, 1994; van der Vegt et al., 2012). However, direct geophysical evidence linking such landforms to the offshore occurrence of freshened porewaters has been lacking. Here, we use newly acquired time-domain controlled-source electromagnetic (TD-CSEM) and co-located high-resolution seismic reflection data (Figure 1) to examine the relationships between subglacial morphology, stratigraphy, and resistivity in the southeastern North Sea. This approach enables, for the first time in this region, an assessment of the spatial extent and controlling factors of OFG within a formerly glaciated shelf.

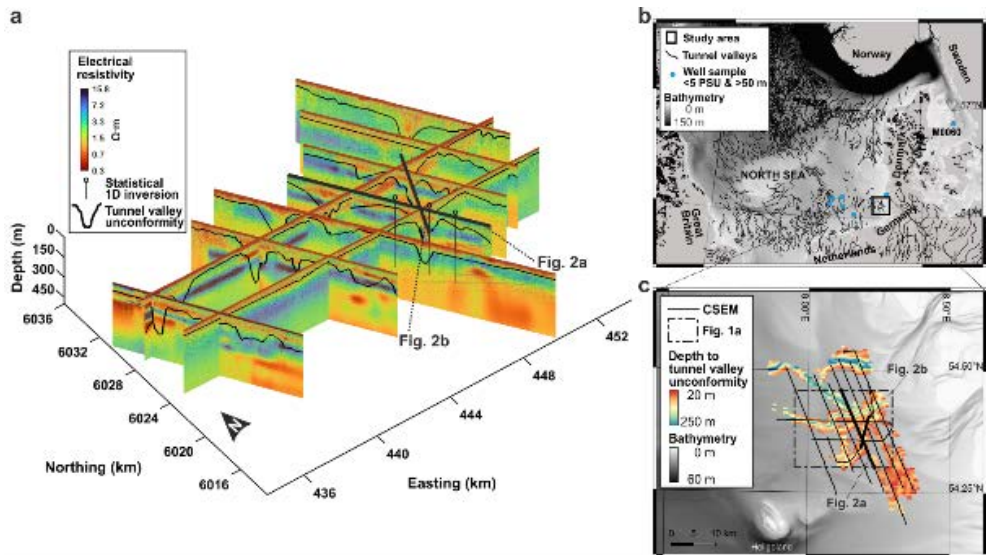


Figure 1: Electrical resistivity structure and subglacial landforms of the southeastern North Sea. (a) Resistivity models from surface-towed TD-CSEM profiles shown in 3D perspective, overlain on co-located high-resolution seismic lines. A laterally continuous, depth-limited elevated-resistivity band is imaged across multiple stratigraphic units and tunnel valleys. (b) Regional overview of the North Sea showing the widespread distribution of tunnel valleys formed by pressurized meltwater beneath Pleistocene ice sheets (Clark et al., 2018; Lutz et al., 2009; Ottesen et al., 2020; van der Vegt et al., 2012). (c) Detailed bathymetric map of the study area northwest of Heligoland in the North Sea, with surveyed CSEM profiles (black lines) and mapped tunnel valley unconformity (coloured shading) used in Figure 1a (Lohrberg et al., 2022). Note that the depth to tunnel valley unconformity is referenced to sea-level for better comparison with seismic profiles.

Methods

A surface-towed time-domain controlled-source electromagnetic (TD-CSEM) survey was conducted in the southeastern North Sea between Amrum and Heligoland, covering ~320 km of profiles within a 35 × 25 km area (Figure 1). The modular SWAN system (Pastoressa et al., 2023) consisted of a 100 m horizontal electric-dipole transmitter and two inline receivers towed 250 m and 500 m

behind the transmitter. Electrode and receiver positions were logged by GPS buoys. The transmitter produced a 2 s square waveform at 36 V and 25 A with a 50 % duty cycle.

Data preprocessing included GPS time-synchronization, transient selection and filtering, DC-offset correction, and error estimation. Processed responses were inverted using an extended time-domain version of MARE2DEM (Key, 2016; Haroon et al., 2018), with fixed resistivities for air ($10^8 \Omega\cdot\text{m}$) and seawater ($0.3 \Omega\cdot\text{m}$). A horizontal-to-vertical smoothness ratio of 100 balanced data fidelity and model smoothness.

Selected stations were re-inverted using a Bayesian 1D framework (Blatter et al., 2019) implemented with EMPYMOD (Werthmüller, 2017) to obtain probability density functions for vertical resistivity distributions. This statistical approach validates the main 2D Occam results and provides uncertainty quantification.

Regional subsurface architecture and resistivity distribution

Integration of TD-CSEM resistivity models with seismic reflection profiles reveals a strong link between subglacial landforms and subseafloor resistivity structure (Figure 1). Tunnel valleys incise deeply into Pleistocene–Eocene sequences and locally intersect salt-tectonic structures (Huuse & Lykke-Andersen, 2000; Wenau & Alves, 2020). Fine-grained upper fills display low resistivities ($<1 \Omega\cdot\text{m}$), whereas underlying units exhibit elevated values. Across all ten profiles, a laterally extensive resistive band ($8\text{--}14 \Omega\cdot\text{m}$) occurs between ~ 100 and 250 m bsf, crossing multiple stratigraphic units and maintaining continuity over tens of kilometres. Bayesian 1D inversions validate the depth and thickness of this feature and sharpen vertical contrasts relative to 2D inversions.

Extensive regional resistivity anomalies indicate widespread subglacial meltwater emplacement

Resistivities exceeding $8 \Omega\cdot\text{m}$ require pore-fluid salinities of only 3.5–16 PSU even at low porosities (20 %), confirming that reduced salinity, not compaction, drives the observed anomalies (Figure 2; Archie, 1942; Michael et al., 2016). The band's continuity across lithological boundaries rules out meteoric infiltration through overlying marine clays and instead points to subglacial flushing under high hydraulic heads during ice-sheet advances (Boulton et al., 1993; Piotrowski, 1994, 2007). Repeated glacial cycles re-established pressure gradients, producing multiple pulses of meltwater infiltration into permeable Miocene–Pleistocene sediments. The result is a laterally coherent, depth-limited OFG body preserved beneath postglacial marine deposits.

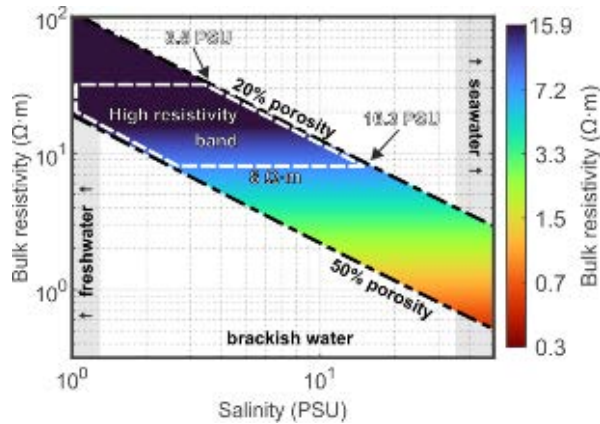


Figure 2: Relationship between bulk resistivity, porosity, and porewater salinity. Archie's law conversion showing resistivity-salinity fields for porosities between 20 and 50 percent. The elevated resistivity band observed in CSEM data (8–14 $\Omega\cdot\text{m}$; dashed box) requires porewater salinities well below that of seawater (~35 PSU), corresponding to brackish to near-freshwater conditions (3.5–16.3 PSU). This implies that low-salinity pore fluids are the dominant control on resistivity in our data inside the band of elevated resistivities.

Integrating geophysical data with borehole and sediment core records

Borehole evidence from IODP Expedition 347 near Anholt (Andrén et al., 2015) reveals low-salinity porewaters (2–10 PSU) at 20–150 m depth within and around tunnel valleys, closely matching the depth of the resistive band. Complementary PINTA survey data (Federal Maritime and Hydrographic Agency, 2025) show <5 PSU porewaters at comparable depths across the southern North Sea. These records corroborate our geophysical interpretation and indicate that freshwater emplacement by subglacial flushing extended across much of the North Sea–Baltic shelf system.

Implications for offshore freshened groundwater systems globally

The discovery of a continuous OFG body beneath the southeastern North Sea demonstrates that subglacial meltwater flushing can create regionally extensive freshwater systems, transcending individual tunnel valleys. Subglacial landforms therefore provide predictive proxies for identifying OFG beneath formerly glaciated shelves. Comparable high-resistivity features reported on the U.S. Atlantic margin (Gustafson et al., 2019) and in the Canadian Maritimes (Person et al., 2003) suggest a global process. Quantifying this resource will require basin-scale integration of electromagnetic, seismic, and hydrogeochemical data, but the evidence presented here establishes a transferable framework for assessing OFG in glaciated continental margins worldwide.

References

- Andrén T, Jorgensen BB, Cotterill C, Green S, Andrén E, Ash J, Bauersachs T, Cragg B, Fanget AS, Fehr A, et al., Expedition 347 summary, Proceedings of the Integrated Ocean Drilling Program 2015, 347, 1–66.
- Archie GE, The electrical resistivity log as an aid in determining some reservoir characteristics, Transactions of the AIME 1942, 146, 54–62.
- Blatter D, Key K, Ray A, Gustafson C & Evans R, Bayesian joint inversion of controlled source electromagnetic and magnetotelluric data to image freshwater aquifer offshore New Jersey, Geophysical Journal International 2019, 218, 1822–1837.
- Boulton GS, Slot T, Blessing K, Glasbergen P, Leijnse T & van Gijssel K, Deep circulation of groundwater in overpressured subglacial aquifers and its geological consequences, Quaternary Science Reviews 1993, 12, 739–745.
- Clark CD, Ely JC, Greenwood SL, Hughes ALC, Meehan R, Barr ID, Bateman MD, Bradwell T, Doole J, Evans JDA, Jordan CJ, Monteys X, Pellicer XM & Sheehy M, BRITICE Glacial Map, version 2, a map and GIS database of glacial landforms of the last British–Irish Ice Sheet, Boreas 2018, 47, 11–e8.
- Cohen D, Person M, Wang P, Gable CW, Hutchinson D, Marksamer A, Dugan B, Kooi H, Groen K, Lizarralde D, Evans RL, Day-Lewis FD & Lane JW, Origin and extent of fresh paleowaters on the Atlantic continental shelf, USA, Ground Water 2010, 48, 143–158.
- Federal Maritime and Hydrographic Agency, PINTA - Data Hub Preliminary Investigation of Sites 2025.
- Haroon A, Hölz S, Weymer B, Tezkan B & Jegen M, Calculating Time-Domain Controlled Source Electromagnetic Signals with MARE2DEM, 3rd Applied Shallow Marine Geophysics Conference 2018, 1–5.
- Hinsby K, Harrar WG, Nyegaard P, Konradi PB, Rasmussen ES, Bidstrup T, Gregersen U & Boaretto E, The Ribe Formation in Western Denmark - Holocene and Pleistocene groundwaters in a coastal Miocene sand aquifer, Geological Society Special Publication 2001, 189, 29–48.
- Huuse M & Lykke-Andersen H, Overdeepened Quaternary valleys in the eastern Danish North Sea: Morphology and origin, Quaternary Science Reviews 2000, 19, 1233–1253.
- Key K, MARE2DEM: a 2-D inversion code for controlled-source electromagnetic and magnetotelluric data, Geophysical Journal International 2016, 207, 571–588.

Kooi H & J Groen, Offshore continuation of coastal groundwater systems; predictions using sharp-interface approximations and variable-density flow modelling, *Journal of Hydrology* 2001, 19–35.

Lohrberg A, Schwarzer K, Unverricht D, Omlin A & Krastel S, Architecture of tunnel valleys in the southeastern North Sea: new insights from high-resolution seismic imaging, *Journal of Quaternary Science* 2020, 35, 892–906.

Lohrberg A, Schneider von Deimling J, Grob H, Lenz KF & Krastel S, Tunnel valleys in the southeastern North Sea: More data, more complexity, *E&G Quaternary Science Journal* 2022.

Lutz R, Kalka S, Gaedicke C, Reinhardt L & Winsemann J, Pleistocene tunnel valleys in the German North Sea: spatial distribution and morphology, *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften* 2009, 160, 225–235.

Meisler H, Leahy PP & Knobel LL, The Effect of Eustatic Sea-Level Changes on Saltwater-Freshwater in the Northern Atlantic Coastal Plain, US Government Printing Office 1984.

Micallef A, Person M, Berndt C, Bertoni C, Cohen D, Dugan B, Evans R, Haroon A, Hensen C, Jegen M, Key K, Kooi H, Liebetrau V, Lofi J, Mailloux BJ, Martin-Nagle R, Michael HA, Müller T, Schmidt M, Schwalenberg K, Trembath-Reichert E, Weymer B, Zhang Y & Thomas AT, Offshore Freshened Groundwater in Continental Margins, *Reviews of Geophysics* 2021, 59, 1–54.

Michael HA, Scott KC, Koneshloo M, Yu X, Khan MR & Li K, Geologic influence on groundwater salinity drives large seawater circulation through the continental shelf, *Geophysical Research Letters* 2016, 43, 10,782–10,791.

Ottesen D, Stewart M, Brønner M & Batchelor CL, Tunnel valleys of the central and northern North Sea (56°N to 62°N): Distribution and characteristics, *Marine Geology* 2020, 425, 106199.

Pastoressa AE, Haroon A, Everett ME, Rohde L, Bartels T, Wollatz-Vogt M, Faghih Z, Franz GK & Micallef A, SWAN: A surface-towed modular Controlled Source Electromagnetic (CSEM) System for mapping submarine groundwater discharge and offshore groundwater resources, *The Leading Edge* 2023, 42, 590–597.

Person M, Dugan B, Swenson JB, Urbano L, Stott C, Taylor J & Willett M, Pleistocene hydrogeology of the Atlantic continental shelf, New England, *GSA Bulletin* 2003, 115, 1324–1343.

Piotrowski JA, Tunnel-valley formation in northwest Germany-geology, mechanisms of formation and subglacial bed conditions for the Bornhöved tunnel valley, *Sedimentary Geology* 1994, 89, 107–141.

Piotrowski JA, Groundwater Under Ice Sheets and Glaciers, *Glacier Science and Environmental Change* 2007, 50–60.

Post VEA, Groen J, Kooi H, Person M, Ge S & Edmunds WM, Offshore fresh groundwater reserves as a global phenomenon, *Nature* 2013, 504, 71–78.

Sandersen PBE & Jørgensen F, Buried Quaternary valleys in western Denmark-occurrence and inferred implications for groundwater resources and vulnerability, *Journal of Applied Geophysics* 2003, 53, 229–248.

Siegel J, Person M, Dugan B, Cohen D, Lizarralde D & Gable C, Influence of late Pleistocene glaciations on the hydrogeology of the continental shelf offshore Massachusetts, USA, *Geochemistry, Geophysics, Geosystems* 2014, 15, 4651–4670.

van der Vegt P, Janszen A, Moscariello A, van der Vegt, Janszen A & Moscariello A, Tunnel valleys: current knowledge and future perspectives, *Geological Society, London, Special Publications* 2012, 368, 75 LP – 97.

Wenau S & Alves TM, Salt-induced crestal faults control the formation of Quaternary tunnel valleys in the southern North Sea, *Boreas* 2020, 49, 799–812.

Werthmüller D, An open-source full 3D electromagnetic modeler for 1D VTI media in Python: *empymod*, *Geophysics* 2017, 82, WB9–WB19.

Scientific Output

List of Publications

Lohrberg A, Haroon A, Moosdorf N, Grob H, Hadré E, Wallmeier C, Pastoressa AE, Micallef A & Krastel S, Subglacial landforms as proxy for offshore freshened groundwater (in prep).

List of conference presentations

2024 | **Resistivity anomalies in tunnel valleys of the North Sea** Electromagnetic Induction Workshop, Beppu, Japan.

2025 | **Resistivity anomalies in buried subglacial landforms and Plio-Pleistocene sediments of the southeastern North Sea revealed by surface-towed time-domain CSEM measurements** EGU2025, Vienna, Austria.

2025 | **The role of buried tunnel valleys of the southeastern North Sea for offshore freshened groundwater: New insights from surface-towed time-domain CSEM measurements** EGU2025, Vienna, Austria.

Data

n/a

Cruise Report

AL611: https://doi.org/10.3289/CR_AL611

EMB283

Vibrio vulnificus proliferation in the Baltic Sea

Authors

Leibniz Institute for Baltic Sea Research Warnemünde (IOW) | Warnemuende, Germany

D. Riedinger, S. Kube, E. Stohr, K. Rose, I. Bollmann, M. Sierks, M. Labrenz

Department of Biology, University of Copenhagen | Helsingør, Denmark

V. Fernández-Juárez

Background

Due to climate change, the pathogen *Vibrio vulnificus* is proliferating along the Baltic coast, posing a threat to human health, tourism, and aquaculture (Baker-Austin et al., 2017; Frank et al., 2006; Ruppert et al., 2004). Previous studies have suggested a positive relationship between the abundance of *V. vulnificus* and water temperature (Baker-Austin et al., 2013), eutrophication, and algal blooms (Eiler et al., 2007), and a negative relationship with the presence of seagrass (Lamb et al., 2017; Reusch et al., 2021). This provides the opportunity for possible local or regional regulation measures of *V. vulnificus*; locally through restoration of seagrass meadows and regionally through reduction of eutrophication levels and consequential algal blooms (Riedinger et al., 2024).

Aim of EMB283

To explore the potential of both of these options we conducted a comparative study of 19 sampling stations, covering Baltic Sea coast salinities from 6 to 15.4, between July and September 2021. As part of a Baltic Sea wide programme in the frame of the EU funded project BaltVib “Pathogenic *Vibrio* bacteria in the current and future Baltic Sea waters: mitigating the problem” within the framework of the BiodivERsA programme “Biodiversity and climate change”, the cruise EMB283 was part of the Baltic Sea sampling campaign. Project partners were from Denmark, Sweden, Finland, Estonia, Lithuania, Poland, and Germany. The main

aim of EMB283 was to analyse the current pelagic and benthic composition of the microbiological community with special focus of *Vibrio* bacteria within and outside of eelgrass meadows, mussel beds and selected macroalgae populations in the salinity gradient of shallow coastal waters of the Baltic Sea. The sampling campaign mainly addressed the questions: 1) What is the in situ distribution of *Vibrio* species in relation to environmental factors? 2) How do special habitats such as eelgrass meadows, mussel beds and selected macroalgae populations influence *Vibrio* distribution in the Baltic Sea? 3) Which environmental factors regulate the pathogenicity of *Vibrio* species?

EMB283 cruise

To answer these questions, R/V ELISABETH MANN BORGESE operated in territorial waters of Germany, Finland, and Estonia across a mesohaline salinity gradient (Figure 1).



Figure 1: Track of R/V Elisabeth Mann Borgese cruise EMB283.

A total of ten stations were sampled for microbiological community composition (Figure 2), hydrophysical and hydrochemical environmental factors as well as for habitat structure of eelgrass meadows and macroalgae habitats, respectively (Figure 3). Due to the limited depth distribution of the target habitats, stations were located in a depth range of 1–10 m less than 1 nm from the shore. Sampling was done from the working boat KLAASHAHN by research divers (Figure 4).

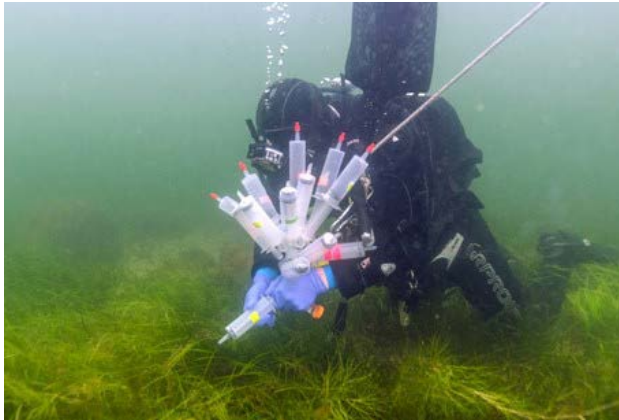


Figure 2: Water sampling for microbiological analyses (© Stohr/IOW).



Figure 3: Measuring eelgrass leave lengths (© Stohr/IOW).



Figure 4: Deploying the working boat Klaashahn from EMB (© Kube/IOW).

Each of the 10 BaltVib sampling stations was divided into three sub-stations. One of these three sub-stations was always located within a certain target habitat (eelgrass, macroalgae or blue mussel population), one of them app. 15 m upstream from the edge of the target habitat and one control station app. 100 m from the edge of the target habitat.

Results

Best *V. vulnificus* predictors were eutrophication-related features such as particulate organic carbon and nitrogen, as well as the occurrence of potentially blooming phytoplankton and associated species. *V. vulnificus* abundance did not vary significantly between vegetated and non-vegetated areas, which was generally supported by data retrieved for three coastal sites with salinities from 6 to 21 in Finland, Germany, and Denmark, where the seasonal occurrence of *Vibrio* spp. was investigated from May to October 2022.

Conclusion

In summary, the EMB283 study has made a significant contribution to understanding the relationship between ecosystem engineers and *V. vulnificus* in the Baltic Sea. The key take-home message is that eutrophication plays a significant, albeit indirect, role in controlling *V. vulnificus*.

References

- Baker-Austin C, Trinanès J, González-Escalona N & Martínez-Urtaza J, Non-Cholera Vibrios: The microbial barometer of climate change, Trends Microbiol, 2017, 25(1),76–84, Epub 2016 Nov 12, PMID: 27843109, doi: 10.1016/j.tim.2016.09.008.
- Frank C, Littman M, Alpers K & Hallauer J, *Vibrio vulnificus* wound infections after contact with the Baltic Sea, Germany, Euro Surveill, 2006, 17, 11(8):E060817.1. doi: 10.2807/esw.11.33.03024-en, Erratum in: Euro Surveill. 2006, 11(8):E060824.5. PMID: 16966781.
- Lamb JB, van de Water JA, Bourne DG, Altier C, Hein MY, Fiorenza EA, Abu N, Jompa J & Harvell CD, Seagrass ecosystems reduce exposure to bacterial pathogens of humans, fishes, and invertebrates, Science, 2017, 17, 355(6326), 731–733, PMID: 28209895, doi: 10.1126/science.aal1956.

Reusch TBH, Schubert PR, Marten SM, et al., Lower *Vibrio* spp. abundances in *Zostera marina* leaf canopies suggest a novel ecosystem function for temperate seagrass beds, Mar Biol 2021, 168, 149, <https://doi.org/10.1007/s00227-021-03963-3>.

Riedinger DJ, Fernández-Juárez V, Delgado LF, Sperlea T, Hassenrück C, Herlemann DPR, Pansch C, Kataržytė M, Bruck F, Ahrens A, Rakowski M, Piwosz K, Stevenson A, Reusch TBH, Gyraite G, Schulz-Bull D, Benterbusch-Brockmüller H, Kube S, Dupke S, Andersson AF, Riemann L & Labrenz M, Control of *Vibrio vulnificus* proliferation in the Baltic Sea through eutrophication and algal bloom management, Commun Earth Environ 2024, 5, 246, <https://doi.org/10.1038/s43247-024-01410-x>.

Ruppert J, Panzig B, Guertler L, et al., Two cases of severe sepsis due to *Vibrio vulnificus* wound infection acquired in the Baltic Sea, Eur J Clin Microbiol Infect Dis 2004, 23, 912–915, <https://doi.org/10.1007/s10096-004-1241-2>.

Scientific Output

List of Publications

Riedinger D, Hassenrück C, Herlemann DPR & Labrenz M, Global distribution and predictive modeling of *Vibrio vulnificus* abundance, Comm Earth Env 2025, 6, 210, <https://doi.org/10.1038/s43247-025-02182-8>.

Herlemann DPR, Delgado LF, Riedinger D, Fernández Juárez V, Käiro K, Andersson AF, Pansch-Hattig C, Riemann L, Bengtsson MM, Gyraitė G, Kataržytė M, Kisand V, Kube S, Martin G, Piwosz K & Labrenz M, Low impact of *Zostera marina* meadows on sediment and water microbiota under brackish conditions, Environ Microbiome 2025, 20, 2, <https://doi.org/10.1186/s40793-024-00662-6>.

Gyraitė G, Kataržytė M, Bučas M, Kalvaitienė G, Kube S, Herlemann DPR, Pansch C, Andersson A F, Pitkanen T, Hokajärvi A-M, Annus-Urmet A, Hauk G, Hippelein M, Lastauskienė E & Labrenz M, Epidemiological and environmental investigation of the ‘big four’ *Vibrio* species, 1994 to 2021: a Baltic Sea retrospective study, Euro Surveill 2024; 29(32), pii=2400075, ES.2024.29.32.2400075, <https://doi.org/10.2807/1560-7917>.

Fernández-Juárez V, Riedinger DJ, Gusmao JB, Delgado-Zambrano LF, Coll-García G, Papazachariou V, Herlemann DPR, Pansch C, Andersson AF, Labrenz M & Riemann L, Temperature, sediment resuspension, and salinity drive the prevalence of *Vibrio vulnificus* in the coastal Baltic Sea, mBio 2024, 15:e01569-24, <https://doi.org/10.1128/mbio.01569-24>.

Riedinger DJ, Fernández-Juárez V, Delgado LF, Sperlea T, Hassenrück C, Herlemann DPR, Pansch C, Kataržytė M, Bruck F, Ahrens A, Rakowski M, Piwosz K, Stevenson A, Reusch TBH, Gyraite G, Schulz-Bull D, Benterbusch-Brockmüller H, Kube S, Dupke S, Andersson AF, Riemann L & Labrenz M, Control of *Vibrio vulnificus* proliferation in the Baltic Sea through eutrophication and algal bloom management, Commun Earth Environ 2024, 5, 246, <https://doi.org/10.1038/s43247-024-01410-x>.

Glackin CC, Dupke S, Chandra TS, Riedinger D & Labrenz M, Combined TCBS and CHROMagar analyses allow for basic identification of *Vibrio vulnificus* within a 48 h incubation period in the coastal Baltic Sea, Microorganism 2024, 12, 614, <https://doi.org/10.3390/microorganisms12030614>.

List of conference presentations

2023 | **Regionally important parameters impact pelagic *Vibrio vulnificus* occurrences along the Baltic Sea coast**, SAME 17 – Symposium of Aquatic Microbial Ecology, Tartu, Estonia

2023 | ***Vibrio vulnificus* can be impacted by regional measures along the Baltic Sea coast, Title of Talk**, BSSC – Baltic Sea Science Conference, Helsinki, Finland

Data

Environmental data:

IOWMeta, <https://doi.io-warnemuende.de/10.12754/data-2023-0010>

Sequencing data:

European Nucleotide Archive, accession number PRJEB682229

Cruise Report

EMB283: https://doi.org/10.48433/cr_emb283

EMB286, EMB290, EMB293, EMB298, EMB305, EMB311, EMB314, EMB317, EMB323 and EMB328

The state of the Baltic Sea in 2022–2023 – ecosystem variability and long-term changes

Authors

Leibniz-Institute for Baltic Sea Research Warnemünde (IOW) | Rostock, Germany
M. Naumann, J. Kuss, V. Mohrholz, P. Holtermann, J. Dutz, J.J. Waniek

The Baltic Sea ecosystem

As a marginal sea with a densely populated catchment area, the Baltic Sea is of great economic and social importance to the countries that border it. The Leibniz Institute for Baltic Sea Research Warnemünde (IOW)'s mission is to provide the knowledge needed to maintain the Baltic's good ecological state. The most severe environmental threats the Baltic Sea faces today are warming, eutrophication and oxygen depletion. The stratification of the water column, resulting from a restricted water exchange, negligible tides and a positive water balance with a freshwater surplus, is one of the main reasons for a slow overturning circulation and the development of so-called extended "dead zones" in the central Baltic Sea. Understanding the development of these balance between freshwater outflow and sporadic inflow of salty oxygenated water, the overturning circulation and its consequences for the ecosystem in terms of both present and future variability, is one of the main aspects of the IOW's long-term observation programme.

The ecosystem state of the year 2022-2023: Meteorological /hydrographic assessment

For the southern Baltic Sea area, the Warnemünde weather station recorded in the winter 2021/2022 a “cold sum” of the air temperature of 15.9 Kd (Kelvin days), which is the time integral of air temperatures below the line $t = 0\text{ }^{\circ}\text{C}$ in Kd. In comparison, the winter 2022/2023 showed a value of 30.8 Kd. Both winter seasons leading to a classification as mild, ranked as sixth and 15th warmest winter since the beginning of recording in 1948. The summer “heat sum’s” of 281.4 Kd (2022) and 288.7 Kd (2023) rank at 8th and 6th position over the past 75 years, but they are far below the record of 394.5 Kd in 2018. The long-term average heat sum is 163 Kd. The heat sum is the corresponding integral above the line $t = 16\text{ }^{\circ}\text{C}$ during the summer months April to October.

In the course of the year 2023, the phase of years (2017–2022) showing weak inflow activity into Baltic Sea was interrupted. A series of inflow events affected the environmental conditions in the different basins of the western Baltic Sea during 2023. Traces of a cold, saline inflow in December 2022 were still visible in the bottom water of the Arkona Basin in February. In early summer, a baroclinic inflow build a thick bottom layer of saline water in the Belt Sea and replaced the cold bottom water in the Arkona Basin by warm, but not exceptionally saline water. During December 2023 intensified inflow activity was recorded, which is classified as mid-sized Major Baltic Inflow (MBI) event after MOHRHOLZ (2018) and imported a salt mass of 1.7 Gt (salinity $>15\text{ g kg}^{-1}$) into the deep water of the Arkona Basin. In 2023, the surface waters in the western Baltic Sea (Darss Sill and Arkona Basin) exhibited temperatures significantly higher than the annual long-term average of $8.8\text{ }^{\circ}\text{C}$ (1900–2005). The winter and autumn water temperatures were about 1.5 K above the monthly long-term average. Summer temperatures, however, remained close to the long-term average, with occasional deviations due to cold anomalies in June and August, likely caused by episodic upwelling events. The partly cool and stormy weather in summer 2023 as well as the minor barotropic inflow event of December 2022 resulted in a consistently good oxygen supply from the Belt Sea to the Arkona Sea (bottom water $> 2\text{ ml l}^{-1}$). The concentration of inorganic nutrients in the surface water was within the range of the previous decade in February 2023. The N/P ratio of the surface water showed a decreasing west-east trend from the Belt Sea to the Bornholm Sea. This pattern was similar to the previous year and confirmed again that nitrogen was a limiting factor in the Baltic Proper, giving diazotrophic cyanobacteria an advantage compared to primary producers that depend on nitrate.

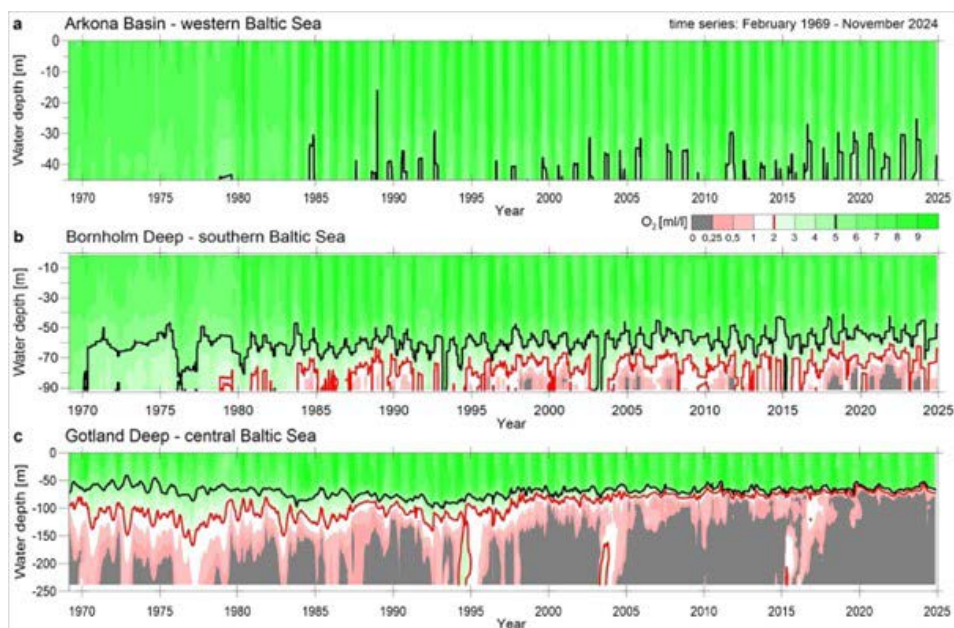


Figure 1: Stagnation and oxygen deficiency are dominating the deep-water layers of the central Baltic Sea. Long-term data series at the key stations Arkona Basin (a), Bornholm Deep (b) and Gotland Deep (c) – concentrations of dissolved oxygen in the water column (1969–2024).

By ongoing accumulation of hydrogen sulphide in deep water of the Gotland Sea, the intensifying of the oxygen deficit and accompanying symptoms continued in 2023. The increase of the oxygen deficit is caused by current eutrophication and produced and subsequently remineralized large amounts of biomass. At Gotland Deep station, the decline of oxygen continued since 2019 and showed an accumulation of hydrogen sulphide equivalent of $317 \mu\text{mol l}^{-1}$ oxygen and at Fårö Deep station of $-171 \mu\text{mol l}^{-1}$ oxygen at respective deep water reference depths in 2023.

The biological state assessment

In 2023, 29 phytoplankton samples were collected at 6 stations located in the Belt Sea (Kiel Bight and Bay of Mecklenburg) and the Arkona Basin. All together 141 phytoplankton taxa were recorded in the Belt Sea and the Arkona Basin with highest number of taxa (89) recorded in November. In 2023, mean annual biomass in the study area was $593,2 \mu\text{g l}^{-1}$. This is significantly lower than in 2022, and below the 20 year mean. Corresponding mean chlorophyll a (Chl a) concentrations of $2,8 \mu\text{g l}^{-1}$ were, however, in the range of previous years. Generally, seasonal Chl a development was uniform and very similar in Belt Sea and Arkona Basin throughout the year, with highest concentrations measured in March and November and lowest in May. The prominent 2023 Chl a peak was

detected in March in Kiel Bight (up to $13 \mu\text{g l}^{-1}$), capturing a fully developed spring bloom leading to the highest annual phytoplankton biomass ($4636 \mu\text{g l}^{-1}$) in 2023. Despite quite uniform Chl a succession patterns in both areas, seasonal dynamics of phytoplankton biomass composition clearly displayed spatial differences, reflecting the marine influence in the Belt Sea and the increasingly brackish character of the Arkona Basin.

The diatom spring bloom in the Belt Sea started in the westernmost Kiel Bight in February, when Chl a concentrations of nearly $3 \mu\text{g l}^{-1}$ corresponding to biomass of $362 \mu\text{g l}^{-1}$, were measured, mostly consisting of diatoms, with *Rhizosolenia* spp. constituting > 70 %. A few weeks later, biomass of diatoms had increased more than 10-fold in the Kiel Bight. In contrast, phytoplankton production was slightly delayed in the Bay of Mecklenburg and generally had significantly lower biomass values. Also, the summer community in the Bay of Mecklenburg was highly dominated by diatoms, though portions of dinoflagellates, Tripos, and cyanobacteria had increased then. Late autumn (November) was the most productive period of the annual phytoplankton cycle in the Bay of Mecklenburg in 2023, as indicated by Chl a concentrations of $4,3 \mu\text{g l}^{-1}$ to $8 \mu\text{g l}^{-1}$ and diatom dominated (> 80 %) biomass concentrations of up to $1390 \mu\text{g l}^{-1}$. In Arkona Basin, the north-east succession of the spring bloom was well reflected by spatial biomass dynamics. Highest annual Chl a ($6,3 \mu\text{g l}^{-1}$ at K5 and $3,6 \mu\text{g l}^{-1}$ at K4) and biomass concentrations ($1168 \mu\text{g l}^{-1}$ at K5 and $228,5 \mu\text{g l}^{-1}$ at K4) were measured in the western and central parts of the Arkona Basin in November. Winter and spring Chl a concentrations decreased prominently towards the east as did biomass. In spring, the Arkona community was generally dominated by *Mesodinium rubrum*. Dinoflagellates and cyanobacteria had high biomass shares (45% and 20 %) in August.

In 2023, 15 potentially toxic or harmful algal taxa were recorded including several warm-water species such as *Karenia mikimotoi*, *Akashiwo sanguinea* and *Karlodinium veneticum*. Cyanobacteria biomass of 2023 was, for the first time, considered in a long-term analysis for the Belt Sea and the Arkona Basin. In the Belt Sea the cyanobacteria biomass was at the 20 year mean, but above the 20 year mean at the central and eastern Arkona stations.

In 2023, the inflows had little influence on the zooplankton species inventory with the number of taxa in the range of previous inflow free years (52 taxa). While a transport of some stenohaline marine taxa such as *Penilia avirostris* into the Arkona Basin was observed, their number was low. In addition, several of the marine and brackish species that were present in preceding, non-inflow years were lacking in 2023 and, thus, the taxa number remained on a lower level. Apart from *Acartia tonsa*, no other species classified as non-indigenous species (NIS) were observed.

The annual average species composition was dominated by copepods in all areas. This is common in the Belt Sea, but unusual in the Arkona Basin where rotifers and cladocerans can show large stocks in spring and summer, respectively. These were lacking in 2023. The decline in their contribution continues a series of similar observations since 2019 and, thus, cannot be attributed to unusual hydrographical situation in 2023.

The seasonal dynamics and the composition of the zooplankton stock in the Kiel Bight and the Bay of Mecklenburg was very similar likely owed to their connection via the Fehmarn Belt. In agreement with winter-spring temperatures that were 2–3 °C above the long-term mean, the zooplankton stock showed an early increase with a doubling of the stock size in March and May, respectively. Copepods, especially the genera *Pseudocalanus* and *Oithona*, dominated the zooplankton followed by polychaete larvae and the appendicularian *Oikopleura*. In summer, the zooplankton stock collapsed to only 15–25 % of the long-term mean. Since the saline and thermal conditions were not exceptional for the area, the decline might be related to a combined stress of very warm temperatures together with the usual food shortage during the summer period. Despite the different hydrography with a lower salinity throughout the water column, the seasonal dynamics and stock composition of the zooplankton in the Arkona Basin resembled those observed in the Belt Sea. The summer collapse of the zooplankton in all areas had only little impact on the long-term variation of the copepods in the western Baltic Sea.

The IOW long-term observation program

The IOW's long-term observation programme collects data on the seasonal and long-term variability of the Bornholm Sea and central Baltic Sea ecosystem's hydrographic, chemical and biological state. This programme is supplemented by observations in the western Baltic Sea, which are conducted as part of the national monitoring programme financed by the Federal Maritime Agency (BSH). The density of the station network is determined by the requirements of physical investigations into the dynamics of water exchange and Baltic Sea circulation. Chemical-biological investigations are limited to a few selected stations. In addition, permanent measuring stations are operated at key locations to complement the spatial data with high temporal resolution. The programme involves 60 days at sea per year, divided into five cruises of approximately 14 days each, and is endorsed by Ocean Decade.

The observation programme has continuously built up time series at key stations since 1969. This long-term data is essential for researching the natural variability of the Baltic Sea ecosystem, anthropogenic influences, and the effects of climate change. They are thus indispensable for fulfilling the IOW's research mission. For example, long-term data series on dissolved oxygen and hydrogen sulphide

concentrations have been used to create distribution maps and analyse trends over the past 50 years (see Figure 1). Furthermore, the data serve as a standard for calibrating and comparing several model results for hypoxic areas in the Baltic Sea. These observations support model studies such as that of KRAPF et al. (2022), which analyse the occurrence of oxygen depletion on longer timescales in the past and future. All data obtained are freely available to researchers and the general public in the IOW's database (IOWDB), the Federal Environment Agency's database (MUDAB), and in an international context, the ICES/HELCOM database. They facilitate cooperation within the Baltic Sea region and beyond.

References

- Dutz J, Zettler ML, Kremp A, Paul C & Kube S, Biological assessment of the Baltic Sea 2023, Marine Science Reports 2025, 129, doi: 10.12754/msr-2025-0129.
- Krapf K, Naumann M, Dutheil C & Meier HEM, Investigating hypoxic and euxinic area changes based on various datasets from the Baltic Sea, Frontiers in Marine Science 2022, doi: 10.3389/fmars.2022.823476.
- Mohrholz V, major Baltic Inflow Statistics – Revised, Frontiers in Marine Science, 5, 2018, doi: 10.3389/fmars.2018.00384.
- Naumann M, Gräwe U, Mohrholz V, Kuss J, Kanwischer M, Osterholz H, Feistel S, Hand I & Waniek JJ, Hydrographic-hydrochemical assessment of the Baltic Sea 2023, Marine Science Reports 2024, 128, doi: 10.12754/msr-2024-0128.
- Naumann M, Gräwe U, Umlauf L, Burchard H, Mohrholz V, Kuss J, Kanwischer M, Osterholz H, Feistel S, Hand I, Waniek JJ, Schulz-Bull DE, et al., Hydrographic-hydrochemical assessment of the Baltic Sea 2022, Marine Science Reports 2024, 127, doi: 10.12754/msr-2024-0127.
- Zettler M L, Kremp A & Dutz J, Biological assessment of the Baltic Sea 2022, Marine Science Reports 2024, 125, doi: 10.12754/msr-2024-0125.

Scientific Output

Data

All physical oceanographic and chemical data can be investigated and downloaded from the IOW oceanographic database IOWDB at:
institute <https://odin2.io-warnemuende.de/#/>

The data are imported also into the national and international databases MUDAB and ICES.

Cruise Reports

Cruise reports of the IOW long-term observation program are available at
<https://www.io-warnemuende.de/fahrtberichte.html> (for cruises since 2001)

EMB288

Trawl marks in the Baltic Sea Basins: Results from Research Cruise EMB288

Authors

Leibniz Institute for Baltic Sea Research Warnemünde | Warnemünde, Germany
P. Feldens, I. Schulze, M. Schönke

Bottom trawling represents the largest anthropogenic source of physical impact on the seafloor in terms of spatial extent, affecting approximately 15 million km² per year (Oberle et al. 2016). Shelf regions are particularly affected, where trawling has been addressed to lead to a reduced abundance and biomass of benthic flora and fauna (Depestele et al. 2016, Amoroso et al. 2018). Despite this impact, bottom trawling remains one of the most important activities for meeting the global demand for protein-rich food that cannot be matched by terrestrial sources at comparable scales of production and environmental cost (Hilborn et al 2023). Studies have also suggested that bottom-contact fishing could be compatible with the sustainable management of marine ecosystems (Pitcher et al. 2022). In order to achieve this, it needs to be understood how trawling gear physically interacts with the marine environment in order to develop more robust environmental descriptors. The impact on seafloor morphology and seafloor integrity is an essential part of the physical interaction with the seafloor.

Acoustic remote sensing, including multibeam echosounders (MBES) and sidescan sonar (SSS), has emerged as a primary tool for mapping natural and anthropogenic seafloor morphology and features at high spatial resolution and including trawl marks (Schönke et al. 2022). High-resolution mapping of trawling footprints is crucial for addressing knowledge gaps in assessing the effectiveness of spatial management measures, such as marine protected areas, quantifying seafloor regeneration rates following trawling and distinguishing the physical impacts of different gear types. However, objective detection of trawl marks from acoustic data remains challenging. Their morphology varies widely due to differences in gear type, fishing practices, and substrate type. Their appearance ranges from continuous linear scars to discontinuous traces, cross-patterns, or rows of pit-like depressions, sometimes accompanied by lateral mounds formed by excavated material. Multibeam echosounder (MBES) data provide detailed morphology and

incision depth information, but their limited swath width restricts coverage to relatively small survey areas. Side-scan sonar (SSS), in contrast, allows broader coverage but primarily captures textural changes associated with sediment disturbance. Recent advances in machine learning, particularly deep convolutional neural networks, allow their easy application for automated feature detection in geophysical datasets.

Research cruise EMB288 (EQUOTRAWL) was conducted from March 1–4, 2022, aboard RV Elisabeth Mann Borgese. The original objective was to constrain the time required for seafloor disturbed by bottom trawling to return to morphological equilibrium, defined as the condition where bottom trawling impacts are no longer discernible in shipboard acoustic data. The approach involved surveying bottom trawl sites provided by the Thünen Institute of Baltic Sea Fisheries to assign accurate coordinates to the known trawling locations and to confirm the presence of seafloor disturbance, based on reported information about location, gear type, and timing. The goal was to record high-resolution bathymetric data using onboard multibeam echo sounder systems at previously trawled positions to determine whether old trawl marks could still be recognized.

The survey covered 18 stations throughout Mecklenburg Bay and the Fehmarn Belt, utilizing an R2Sonic multibeam echo sounder system configured with a pulse length of 50 microseconds, frequency of 400 kHz, fan angle of 145 degrees, gain setting of 6, and power setting of 209 dB. Survey operations maintained vessel speeds of 4.5–5 knots during data acquisition. Sound velocity profiles were collected at each station using dedicated profiling equipment, and ground-truthing was conducted through Van Veen grab sampling to characterize substrate conditions. In the Fehmarn Belt area, side-scan sonar surveys were conducted in focus areas of the DAM MGF Ostsee pilot study, with the sonar system towed at 19-meter depth at 4.5 knots.

The primary research objectives of EMB288 could not be successfully completed. The fundamental problem was that trawl mark positions recorded during Thünen Institute trawling activities lacked sufficient positional accuracy for reliable relocation using acoustic survey methods at most locations. Relocation could only be achieved with confidence at two of the planned survey locations, deemed insufficient for further analysis. The surveyed areas contained such dense concentrations of overlapping trawl marks from multiple years of fishing activities that individual marks with offsets to the coordinates provided by the Thünen institute could not be confidently assigned to specific trawling events with known timing and gear characteristics.

Despite the challenges in achieving the original research objectives, the comprehensive acoustic dataset collected during EMB288 proved very valuable for advancing automated trawl mark detection methodologies. The high-quality

multibeam bathymetry data were integrated into the MGF project to develop machine learning approaches for systematic trawl mark identification across larger spatial scales. The development of an automated detection system utilized a U-Net convolutional neural network architecture for semantic segmentation of trawl marks in MBES (and side scan sonar data, not recorded during EMB288) datasets. The developed model can identify trawl marks across various seafloor conditions and acoustic data types. Testing in central Mecklenburg Bay has shown reliable detection performance that significantly exceeds manual interpretation capabilities (Figure 1). The automated approach successfully identifies trawl marks across different morphological expressions, from continuous linear scars to discontinuous traces and cross-pattern configurations. The methodology provides a scalable solution for comprehensive trawl mark mapping across the southwestern Baltic Sea, where high-resolution bathymetric grids from the Federal Maritime and Hydrographic Agency (BSH) combined with historical side-scan sonar mosaics reveal abundant evidence of trawling activity, a corresponding paper is currently under preparation.

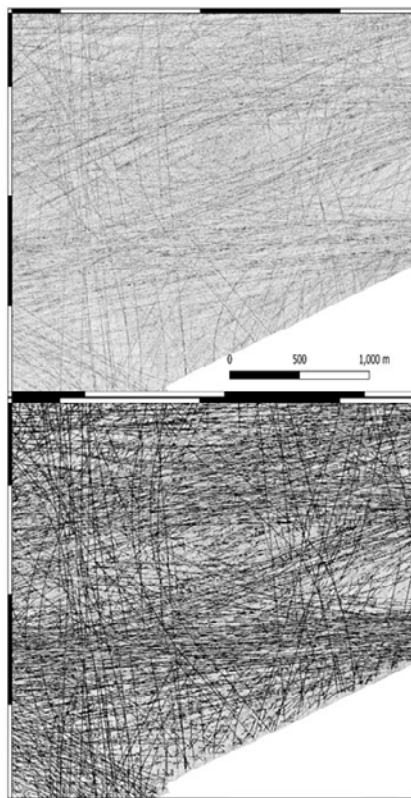


Figure 1: Top: Slope map of central Mecklenburg Bay. Bottom: Automatically delineated trawl marks in the same area. Due to their high density, the repeated survey of single trawl marks requires accurate positional information.

References

Amoroso RO, et al., Bottom trawl fishing footprints on the world's continental shelves, *Proceedings of the National Academy of Sciences* 2018, 115, 10275–10282.

Hilborn R, Amoroso R, Collie J, Hiddink J G, Kaiser M J, Mazon T, McConnaughey R A, Parma AM, Pitcher CR, Sciberras M & Suuronen P, Evaluating the sustainability and environmental impacts of trawling compared to other food production systems, *ICES Journal of Marine Science* 2023, 80, 6, 1567–1579, <https://doi.org/10.1093/icesjms/fsad115>.

Depestele J, Ivanović A, Degrendele K, Esmaeili M, Polet H, Roche M, Summerbell K, Teal LR, Vanellander B & O'Neill FG, Measuring and assessing the physical impact of beam trawling, *ICES Journal of Marine Science* 2016, 73, i15–i26.

Oberle FKJ, Storlazzi CD & Hanebuth TJJ, What a drag: Quantifying the global impact of chronic bottom trawling on continental shelf sediment, *Journal of Marine Systems* 2016, 159, 109–119.

Pitcher CR, et al., Trawl impacts on the relative status of biotic communities of seabed sedimentary habitats in 24 regions worldwide, *Proc. Natl. Acad. Sci. U.S.A.* 2022, 119 (2), e2109449119, <https://doi.org/10.1073/pnas.2109449119>.

Schönke M, Clemens D & Feldens P, Quantifying the Physical Impact of Bottom Trawling Based on High-Resolution Bathymetric Data, *Remote Sensing* 2022, 14, 2782.

Scientific Output

List of Publications

Preprint: Schönke M, Schulze I, Gogina M, von Dorrien C, Oesterwind D & Feldens P, What AIS Misses and Acoustics Reveal: Monitoring Seafloor Disturbance and Recovery from Bottom Trawling in the Southern Baltic Sea Over Five Years, Available at SSRN: <https://ssrn.com/abstract=5381183> or <http://dx.doi.org/10.2139/ssrn.5381183>, currently under review at *Ecological Informatic*.

List of conference presentations

2024 | **Revealing the evolution of trawling activity in the Fehmarn Belt** GeoHab
Conference 2024, Arendal, Norway

Cruise Report

EMB288: https://doi.org/10.48433/cr_emb288

EMB292 and EMB319

Living along gradients – spatiotemporal variability of macrobenthic communities in the southwestern Baltic Sea

Authors

Leibniz Institute for Baltic Sea Research Warnemuende (IOW) | Rostock, Germany
K. Romoth, D. Marx, S. Papenmeier, M.L. Zettler

The living conditions of benthic species and communities in the southwestern Baltic Sea are characterized by a high variability of natural environmental conditions. This variability affects the development cycles of single individuals through its temporal component, as well as the distribution of species and thus the composition of benthic communities through its spatial component. The importance of individual environmental parameters for macrozoobenthos and macrophytobenthos depends mainly on the spatial scale considered. Local effects are mainly influenced by substrate characteristics, as well as biological effects (competition, predation) and flow exposure, while at the regional and supra-regional level, as well as in temporal aspects, the characteristics of the water body have the greatest significance. The most important parameters known to be salinity, temperature, and oxygen content. While local-scale variability leads to the formation of different communities and thus to high local diversity through species specialization, species richness decreases along the salinity gradient. In particular, specialists are absent at low salinities or occupy different ecological niches in areas with lower salinity than in fully marine areas.

In addition to this natural stress, stressors resulting from human activities are increasingly affecting benthic communities. Large-scale effects are caused, for example, by direct and indirect consequences of eutrophication (deterioration of light climate, increase in the frequency, duration and intensity of oxygen deficiency) and by mechanical pressure from bottom-contacting fishing gear. Construction activities, sediment extraction and disposal (legacy sites), as well as additional biological interactions (competition, predation) by introduced species (neobiota) can locally lead to intensive temporary or even permanent changes in benthic habitats. Due to the rapidly increasing pressure, the EU's marine

environmental policy has created a framework for achieving a good environmental status or favorable conservation status of marine organisms and habitats with the Marine Strategy Framework Directive (MSFD) and the Habitats Directive (HD). The implementation of these directives includes a regular assessment of the state of marine ecosystems.

The cruises EMB292 and EMB319 proceeded in the southwestern Baltic Sea between Kiel Bay and Pomeranian Bay and were a sequel of cruises started in 2009 within the framework of subsequent projects funded by the German Federal Agency for Nature Conservation (BfN). One aim has been the implementation of the Habitats Directive and the further development of HD monitoring. Therefore, a long-term data series has been established, assessing the temporal variability and environmental state in special offshore habitats (reefs, sandbanks) in the German Exclusive Economic Zone (EEZ). Another aim has been the investigating of the temporal and spatial variability of endo- and epibenthic communities along different natural and anthropogenic gradients as a basis for the development of monitoring strategies under the frame of the MSFD and for the development of high-resolution maps of benthic biotopes. Sampling of benthic communities was carried out by using a combination of different devices (van Veen grab, dredge, and video).

The hydroacoustic team, participating as secondary user, used free night slots to collect sidescan sonar and multibeam echosounder data with the aim of evaluating temporal and spatial changes in stone density of reefs in parts of the Fehmarn Belt and monitoring the morphological recovery of detonation crater in this area. Further aims were closing gaps in sediment distribution maps within the nature conservation area Adlergrund, collecting data sets to train neural networks for automatic stone detection at the Western Rönnebank and monitoring scouring of large boulders spread by humans on a sandbank in the Bay of Pomerania.

The mapping data resulting from EMB292 and EMB319 (and additional data since 2010) were used to create maps (according to MSFD, HELCOM HUB) for the entire German Baltic Sea at a high spatial resolution of 1 km. In three nature conservation areas of the EEZ and selected focus areas in the coastal waters, resolution even reaches 50 m x 50 m. Spatial delineation of benthic biotopes and communities was achieved by utilizing predictive habitat modeling. The resulting maps provide a new level of spatial detail and are the essential basis for future monitoring, status assessment as well as for protection and management measures.

The benthic data collected were also included in the 2024 HD assessment, which covers a six-year reporting period and aims to account for successes, identify areas requiring action, and provide insights into the effectiveness of the Natura 2000 network.

The results indicated that the pressure of use remains high in the Baltic Sea due to numerous stressors. The conservation status of many habitats such as submerged sandbanks and reefs was classified unfavorable in this last assessment. Regarding the evaluation criteria of habitat structure and species inventory considered in the monitoring, no trends could be observed so far that could lead to a change in the evaluation.

Scientific Output

List of Publications

Gogina M, Hahn SJ, Ohde R, Brandt A, Forster S, Kröncke I, Powilleit M, Romoth K, Sonnewald M & Zettler ML, Baseline inventory of benthic macrofauna in German marine protected areas (2020–2022) before closure for bottom-contact fishing, *Biology* 2024, 13(6), 389, doi:10.3390/biology13060389.

Marx D, Feldens A, Papenmeier S, Feldens P, Darr A, Zettler ML & Heinicke K, Habitats and Biotopes in the German Baltic Sea, *Biology* 2024, 13, 6, <https://doi.org/10.3390/biology13010006>.

Romoth K, Darr A, Papenmeier S, Zettler ML & Gogina M, Substrate heterogeneity as a trigger for species diversity in marine benthic assemblages, *Biology* 2023, 12, 825, doi: 10.3390/biology12060825.

Romoth K, Gogina M, Beisiegel K, Darr A & Zettler ML, First record of the common sun star *Crossaster papposus* (L., 1767) in the Baltic Sea in over 100 years, *Oceanological and Hydrobiological Studies* 2022, 51, 143–148, doi: 10.26881/oandhs-2022.2.02.

Schulz LA, Gogina M, Friedland R, Wolf F, Kniesz K & Zettler ML, Recent distribution and population structure of the ocean quahog, *Arctica islandica* (Linnaeus, 1767), in the German waters of the Baltic Sea – Ecological insights and relevance for conservation, *Journal of Sea Research* 2025, 208, 102630, doi:10.1016/j.seares.2025.102630.

List of conference presentations

2023 | **Biotopkarten der Ostsee [Biotope maps of the Baltic Sea]** BfN-Kolloquium Meeresnaturschutz, Vilm, Germany.

Data

SSS raw data:

available on request through the State Office for Environment, Nature Conservation and Geology Mecklenburg-Western Pomerania (LUNG MV) or the IOW geo database

Benthic macrofauna data:

available on request through the Federal agency for Nature conservation (BfN) or the IOW Macrozoobenthos database

Cruise Reports

EMB292: https://doi.org/10.48433/cr_emb292

EMB319: https://doi.org/10.48433/cr_emb319

EMB295

Central Baltic Sea Air-Sea Gas Exchange Experiment

Authors

Leibniz Institute for Baltic Sea Research Warnemuende (IOW) | Rostock, Germany

H. Bittig, M. Björner, J. Donath, H. Czerski, R. Dobashi, E. Gorman, D. Ho, J. Karnatz, C. Marandino, G. Rehder, B. Sabbagzadeh, T. Steffens, T. Streitz

The Central Baltic Sea Air-Sea Gas Exchange (CenBASE) cruise EMB295 investigated the air-sea gas exchange (ASE) in the Baltic Sea. Air-sea gas exchange influences the cycling of biogeochemically important trace gases on global and regional scales (CO_2 , CH_4 , N_2O , DMS, halocarbons, and non-methane hydrocarbons), and affects water quality on local scales (e. g., oxygen exchange). Wind speed is typically used to parameterize gas transfer. Advancements in the last few decades have helped to narrow down the list of reasonable wind speed/ASE parameterizations that are applicable in most circumstances over the ocean. In the Baltic Sea, however, existing parameterizations might not be applicable, because wind fetch and wave development are different, high primary production can lead to unusually high concentrations of surfactants, and intermediate salinities (brackish waters) lead to bubble cloud characteristics different from that of fresh- or seawater.

The specific questions addressed during the Central Baltic Sea Air-Sea Gas Exchange cruise EMB295 were therefore:

1. Can open ocean wind speed/gas exchange parameterizations be applied to the central Baltic Sea, or is a specific ASE-parameterization required?
2. Do the differences in gas transfer velocities measured with the $^3\text{He}/\text{SF}_6$ - and Eddy covariance (EC) CO_2 -techniques observed in the open ocean exist in the Baltic Sea?
3. Does the study support the idea of a bias in the calculation of the net CO_2 flux based on higher abundance of surfactants during the productive period?

4. Can the observations at the site and during transit (EC) hint to a deviation from established ASE parameterizations due to the brackish water characteristic of the Central Baltic Sea?

To this end, a multi-method approach was followed during cruise EMB295 by

- a. using both the $^3\text{He}/\text{SF}_6$ dual tracer technique and direct eddy covariance flux measurements of DMS and CO_2 in order to measure air-sea gas exchange fluxes,
- b. continuous monitoring of the surface concentrations of CO_2 , CH_4 , and N_2O to allow a comparison of flux estimates based on our findings and the range of published parameterizations for the three major greenhouse gases,
- c. investigating the abundance and characteristics of surfactants and organic compounds in the surface microlayer (e. g., colored dissolved organic matter (CDOM), fluorescent dissolved organic matter (FDOM), transparent exopolymer particles (TEP), Coomassie-stainable particles (CSP), proteins, and polysaccharides) as well as phytoplankton and cyanobacteria abundance to assess their potential impact on ASE,
- d. determining water column structure by shipboard CTD measurements, and
- e. using a surface drift-buoy mounted bubble camera and acoustic backscatter to investigate bubble plume dynamics and bubble size distribution within the top metres of the ocean.
- f. Moreover, the GODESS profiling mooring was deployed in the central Gotland basin to provide high-resolution measurements of surface turbulence and water column structure in the upper water column. but did not operate in the field as planned.

The central Baltic Sea's Eastern Gotland basin was selected as main working area being representative for a large area of the Baltic Sea with respect to its surface water characteristics (bathymetry/geometry, brackish water characteristics, and the presence of surfactants), and being one of the most dynamic area in terms of pCO_2 variations. The surface salinity of around 7 is at the edge of the range where an enhanced bubble-mediated gas transfer has been demonstrated in a previous study (Anguelova and Huq, 2017), but characteristic for a very large part of the Baltic Sea. The marine environment is expected to be minimally disturbed by the conducted research activities. The $^3\text{He}/\text{SF}_6$ tracers are inert and evade by ASE over short timescales. The cruise activities followed the principles as stated in the Declaration of Responsible Research.

The cruise started late as a key participant had to clear the Covid-19 requirements before boarding, and it was interrupted in its second half to get medical assistance on shore. Despite the shortening, all cruise participants were able to deploy their instruments and get valuable data and experience for further work, some of which is going to be presented.

We thank the captain and crew of R/V ELISABETH MANN BORGESE for their support and help during this cruise. Our thanks extends to Marcel Deeke (Briese Research). Without the experience and support of Susanne Schöne (IOW) with demanding custom issues the cruise could not have happened.

EMB297

Hot Spots and Moments of C and N turnover in Planktonic Food Webs at the End of Summer

Authors

Leibniz Institute for Baltic Sea Research Warnemuende (IOW) | Rostock, Germany

N. Loick-Wilde, I. Liskow, V. Mohrholz

Universidad de Las Palmas de Gran Canaria | Telde, Spain

A. Fernández Carrera

Georgia Institute of Technology | Atlanta, USA

J. P. Montoya

Loss of biodiversity is one of the largest threats to human society (Cardinale et al. 2012; Díaz et al. 2018; Pörtner et al. 2023). The biogeochemical driver of microbial species loss in the ocean is often a change in nitrogen (N) source that induces an alternation of functional groups at the base of the food web, like dominant phytoplankton functional types, but we don't yet fully understand its impact on higher trophic levels in the field (Glibert et al. 2016; Mitra et al. 2014, Steinkopf et al. 2024).

Zooplankton is the most important secondary producer in the ocean as well as energy supplier for pelagic consumers like fish. Fish biomass formation in the sea depends crucially on the secondary production of zooplankton, which depends itself on the primary production of phytoplankton, the carbon transfer efficiency into zooplankton and the number of trophic transfer steps between zooplankton and phytoplankton (Lalli and Parsons 1997; Libralato et al. 2008). Field studies on all aspects of community specific secondary production are difficult with existing methods. This makes the community-specific secondary production, which can range in orders of magnitude between 0.01 to 1000 mg C m⁻² day⁻¹, the single least understood process in biogeochemical models (Ratnarajah et al. 2023; Rohr et al. 2023).

A late summertime, early fall cruise between 20.08.–02.09 2022 (Figure 1) was chosen to investigate carbon (C) and nitrogen (N) turnover processes in the

planktonic food web. The timing of the cruise was chosen to investigate how the deepening of the thermocline with the anticipated onset of fall mixing impacts primary- and secondary production as well as carbon transfer efficiency into zooplankton across different functional communities of phytoplankton typically found in the different basins of the Baltic Sea in summer (Figure 1). Onboard, zooplankton from surface waters were fed field phytoplankton amended with $^{13}\text{C}\text{-HCO}_3^-$ at each station. We quantified the uptake of ^{13}C by the phytoplankton communities and the transfer of the ^{13}C tracer from the HCO_3^- -fixing phytoplankton into the organic carbon pool of field zooplankton communities using Elemental Analysis-Isotope Ratio Mass Spectrometry (EA-IRMS).

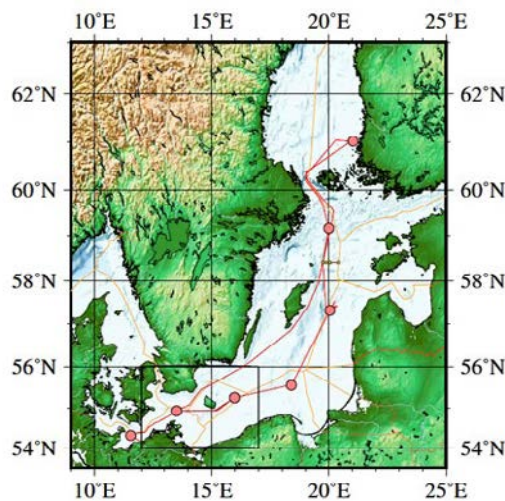


Figure 1: Track chart of RV ELISABETH MANN BORGESE Cruise EMB297. Seven main working areas: Western Baltic: TF12; Arkona Basin: TF113; Bornholm Basin: TF213; Southern Gotland Basin: TF259; Eastern Gotland Basin: TF271; Northern Gotland Basin: NAC1; Bothnian Bay: NAC2. Stations TF113 and TF213 were revisited after a gale on the 28./29. August 2025 (Figure 2).

Mass-specific total organic carbon incorporation rates of the ^{13}C tracer was calculated for phytoplankton, in the following called primary production (PP), and for zooplankton, in the following called secondary production (SP). Highest incorporation of ^{13}C was found in zooplankton at station TF113, characterized by diatoms and dinoflagellates, followed by animals from station TF271, characterized by unpalatable cyanobacteria and haptophytes (Figure 3). The underlying physico-chemical mechanism at station TF113 may have been a westward outflow of surface water from the Bornholm Sea into the Arkona Basin shortly before our trip. This also transported some of the remaining colder winter water from the Bornholm Basin to the Arkona Basin. Visible in the Scanfish (SF) section as a cold (8°C) but low-salinity water mass at a depth of 20 m at station TF113 and TF113B (Figure 2C, B). This water mass should have retained some nutrients from the

previous winter, which were then transported to the surface by wind mixing. This is supported by enhanced nitrate ($0.25 \mu\text{M}$) and ammonium ($0.5 \mu\text{M}$) concentrations in surface waters at the beginning of the cruise at station TF113 (Figure 2A) in an otherwise N-depleted, still highly stratified and very warm ($\text{SST} > 20^\circ\text{C}$) Baltic Sea. ADCP-Drifter data from the Gotland Basin (not shown) confirmed earlier observations (Schmale et al., Eglite et al. 2018) that $\text{SST} > 20^\circ\text{C}$ restricts vertical migration of zooplankton from winter into surface waters.

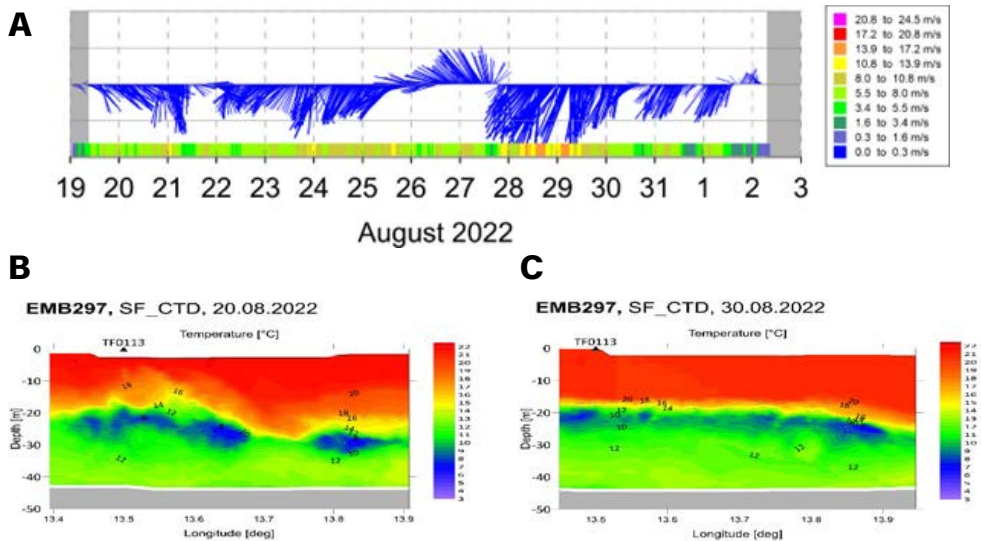


Figure 2: A) Stick plot of wind vector from the ship weather station. B)+C) Temperature distribution along the ScanFish transects across Station TF113 in the Arkona Basin before (B) and after (C) the gale. Only at Stn. 113 before the gale, an upshoaling of subthermocline waters was associated with enhanced nitrate ($0.24 \mu\text{M}$).

Transfer efficiency of carbon into zooplankton, in the following called ecological efficiency (EE), calculated from the SP/PP quotient was extremely low across the Baltic Sea ranging from 0.3% to 10%, with a mean of $2.7 \pm 2.6\%$ (Figure 3). Maximum values of 10% only were found at station TF113B after the gale and at the coastal near station NAC2 in the Bothnian Sea. Values for the direct-feeding proxy $\Delta\delta^{13}\text{C}_{\text{Phyt-Zoo}} > 1 \text{ ‰}$ suggest that at least at a couple of stations (TF113, TF213, TF271, NAC1), lack of direct grazing on phytoplankton contributed to the low EE values. Pending amino acid nitrogen stable isotope analyses will clarify, if enhanced omni- and carnivory can explain the low EE values in mesozooplankton across the Baltic Sea in summer (Loick-Wilde et al. 2019). Significant cyanobacteria biomass shares in the phytoplankton community of the Gotland Basin, where they constituted 46–49% of total phytoplankton biomass at stations TF259 and TF271, respectively (Figure 4, Zettler et al. 2024), may have contributed to the low EE in zooplankton.

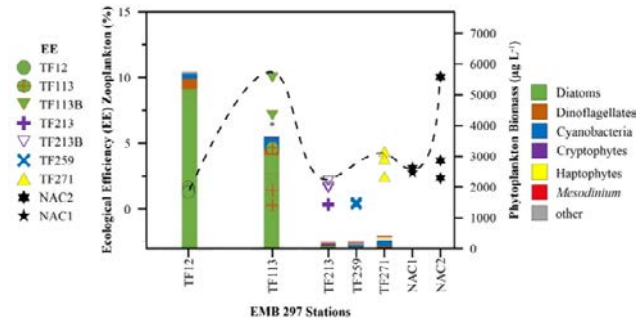


Figure 3: Ecological efficiency (EE) changes in zooplankton from surface waters (%) based on $\delta^{13}\text{C}$ -transfer experiments from micro- to zooplankton across different microplankton communities (Zettler et al. 2024). Surprisingly, EE in late summer/ early fall was highest where diversity of mixotrophs and not diatom biomass was highest.

Finally, osmotrophy may have impacted EE. Osmotrophy is estimated by the uptake of dissolved amino acids by phytoplankton. Interestingly, uptake rates of amino acid nitrogen were in a similar high range as nitrate uptake (Figure 4), with both being in ranges earlier described for the Baltic Sea (Berg et al. 2001). However, the impact of mixotrophic processes like osmotrophy on zooplankton production has not been studied yet. Model and experimental results suggest, that carbon and nitrogen from mixotrophs should be transferred more efficiently into zooplankton (Traboni et al. 2021, Ward and Follows 2016). The tight coupling of amino acid carbon to amino acid nitrogen uptake (C:N of 2.9) associated with osmotrophy compared to a less tight coupling of HCO_3^- to NO_3^- uptake (C:N of 15.0) in phototrophs in our experiments (not shown) support the experimental and model results.

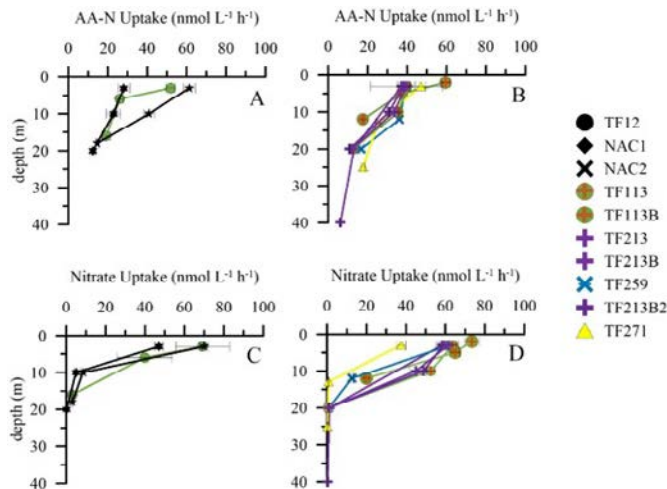


Figure 4: Uptake rates of amino acid nitrogen and nitrate by microplankton at coastal (A, C) and offshore (B, D) stations across the Baltic Sea in late summer during EMB 297. Uptake of both N-sources decreased with depths. Notably, amino acids were actively incorporated by microplankton at rates similar to nitrate uptake.

In summary, the timing of the cruise was well picked as the onset of fall circulation seemed to have started to change the physico-chemical structure of the water column likely by lateral transport and local up shoaling of nutrient-enhanced winter water at the beginning of the cruise and a gale at the end of the cruise. C and N turnover in the planktonic food web reacted to both events by enhanced turnover, which however only resulted in higher EE after the gale. EE was low and likely underestimated. Future EE studies should include transfer of organic carbon via mixotrophs for a more complete picture of the available C pool for zooplankton growth at this critical time of the year for zooplankton overwintering.

References

- Berg GM, Glibert PM, Jorgensen NOG, Balode M & Purina I, Variability in inorganic and organic nitrogen uptake associated with riverine nutrient input in the Gulf of Riga, Baltic Sea, *Estuaries* 2001, 24, 204–214, doi: 10.2307/1352945.
- Cardinale BJ, Duffy JE, Gonzalez A, Hooper DU, Perrings C, Venail P, Narwani A, Mace GM, Tilman D, Wardle DA, Kinzig AP, Daily GC, Loreau M, Grace JB, Larigauderie A, Srivastava DS & Naeem S, Biodiversity loss and its impact on humanity, *Nature* 2012, 486, 59–67, doi: 10.1038/nature11148.
- Díaz S, Pascual U, Stenseke M, Martín-López B, Watson RT, Molnár Z, Hill R, Chan KMA, Baste IA, Brauman KA, Polasky S, Church A, Lonsdale M, Larigauderie A, Leadley PW, van Oudenhoven APE, van der Plaats FE, Schröter M, Lavorel S, Aumeeruddy-Thomas Y, Bukvareva E, Davies K, Demissew S, Erpul G, Failler P, Guerra CA, Hewitt CL, Keune H, Lindley S & Shirayama Y, Assessing nature's contributions to people, *Science* 2018, 359, 270–272, doi: 10.1126/science.aap8826.
- Eglite E, Wodarg D, Dutz J, Wasmund N, Nausch G, Liskow I, Schulz-Bull D & Loick-Wilde N, Strategies of amino acid supply in mesozooplankton during cyanobacteria blooms: a stable nitrogen isotope approach, *Ecosphere* 2018, 9(3), e02135, doi: 10.1002/ecs2.2135.
- Flynn KJ, Mitra A, Anestis K, Anschütz AA, Calbet A, Ferreira GD, Gypens N, Hansen PJ, John U, Martin JL, Mansour JS, Maselli M, Medić N, Norlin A, Not F, Pitta P, Romano F, Saiz E, Schneider LK, Stolte W & Traboni C, Mixotrophic protists and a new paradigm for marine ecology: where does plankton research go now?, *Journal of Plankton Research* 2019, 41(4), 375–391, doi: 10.1093/plankt/fbz026.

Glibert PM, Wilkerson FP, Dugdale RC, Raven JA, Dupont CL, Leavitt PR, Parker AE, Burkholder JM & Kana TM, Pluses and minuses of ammonium and nitrate uptake and assimilation by phytoplankton and implications for productivity and community composition, with emphasis on nitrogen-enriched conditions, *Limnology and Oceanography* 2016, 61, 165–197. doi: <https://doi.org/10.1002/lno.10203>.

Loick-Wilde N, Fernández-Urruzola I, Eglite E, Liskow I, Nausch M, Schulz-Bull D, Wodarg D, Wasmund N & Mohrholz V, Stratification, nitrogen fixation, and cyanobacterial bloom stage regulate the planktonic food web structure, *Global Change Biology* 2019, 25(3), 794–810, doi: [10.1111/gcb.14546](https://doi.org/10.1111/gcb.14546).

Lalli C & Parsons TR, 1997, *Biological oceanography: an introduction*. Elsevier.

Libralato S, Coll M, Tudela S, Palomera I & Pranovi F, Novel index for quantification of ecosystem effects of fishing as removal of secondary production, *Marine Ecology Progress Series* 2008, 355, 107–129, doi: [10.3354/meps07224](https://doi.org/10.3354/meps07224).

Mitra A, Castellani C, Gentleman WC, Jónasdóttir SH, Flynn KJ, Bode A, Halsband C, Kuhn P, Licandro P & Agersted MD, Bridging the gap between marine biogeochemical and fisheries sciences; configuring the zooplankton link, *Progress in Oceanography* 2014, 129, 176–199. doi: [10.1016/j.pocean.2014.04.025](https://doi.org/10.1016/j.pocean.2014.04.025).

Pörtner HO, Scholes RJ, Arneth A, Barnes A, Burrows MT, Diamond SE, Duarte CM, Kiessling W, Leadley P, Managi S, McElwee P, Midgley G, Ngo HT, Obura D, Pascual U, Sankaran M, Shin YJ & Val AL, Overcoming the coupled climate and biodiversity crises and their societal impacts, *Science* 2023, 380, doi:[10.1126/science.abl4881](https://doi.org/10.1126/science.abl4881).

Ratnarajah, L., R. Abu-Alhaija, A. Atkinson, S. Batten, N. J. Bax, K. S. Bernard, G. Canonico, A. Cornils, J. D. Everett, M. Grigoratou, N. H. A. Ishak, D. Johns, F. Lombard, E. Muxagata, C. Ostle, S. Pitois, A. J. Richardson, K. Schmidt, L. Stemmann, K. M. Swadling, G. Yang & Yebra L, Monitoring and modelling marine zooplankton in a changing climate. *Nature Communications* 2023, 14, 564, doi: [10.1038/s41467-023-36241-5](https://doi.org/10.1038/s41467-023-36241-5).

Rohr T, Richardson AJ, Lenton A, Chamberlain MA & Shadwick EH, Zooplankton grazing is the largest source of uncertainty for marine carbon cycling in CMIP6 models, *Commun Earth Environ* 2023, 4, 212, doi: <https://doi.org/10.1038/s43247-023-00871-w>.

Schmale O, Wäge J, Mohrholz V, Wasmund N, Gräwe U, Rehder G, Labrenz M & Loick-Wilde N, The contribution of zooplankton to methane supersaturation in the oxygenated upper waters of the central Baltic Sea, *Limnology and Oceanography* 2018, 63(1), 412–430.

Steinkopf M, Krumme U, Schulz-Bull D, Wodarg D, Loick-Wilde N, Trophic lengthening triggered by filamentous, N₂-fixing cyanobacteria disrupts pelagic but not benthic food webs in a large estuarine ecosystem, *Ecology and Evolution* 2024, 14(2), e11048.

Traboni C, Calbet A & Saiz E, Mixotrophy upgrades food quality for marine calanoid copepods, *Limnol. Oceanogr.* 2021, 66, 4125–4139, doi: 10.1002/lno.11948.

Ward BA & Follows MJ, Marine mixotrophy increases trophic transfer efficiency, mean organism size, and vertical carbon flux, *Proc. Natl. Acad. Sci.* 2016, 113, 2958 LP – 2963, doi: 10.1073/pnas.1517118113.

Zettler ML, Kremp A & Dutz J, Biological assessment of the Baltic Sea,

2022, *Meereswiss. Ber., Warnemünde* 2024, 125, doi:10.12754/msr-2024-0125.

Scientific Output

Cruise Report

EMB297: https://doi.org/10.48433/cr_emb297

EMB306

Paleo-Landscapes of the Darss Sill: Results from research cruise EMB306

Authors

Leibniz Institute for Baltic Sea Research Warnemünde | Warnemünde, Germany
P. Feldens

The postglacial evolution of the southwestern Baltic Sea is characterized by water-level fluctuations and coastline displacements following ice sheet retreat from approximately 17,000 years ago. The Baltic Sea evolved through distinct developmental stages including the glaciolacustrine Baltic Ice Lake (BIL), the glaciomarine Yoldia Sea (YS), the freshwater Ancylus Lake (AL), and the brackish Littorina Sea (LS) (Björck 1995). Understanding this complex history is necessary for paleoenvironmental reconstruction and archaeological prospection, as former terrestrial areas now submerged may host Mesolithic archaeological sites at water depths up to 21 meters below present sea level (Geersen et al. 2024). The Darss Sill represents a key threshold area in the southwestern Baltic Sea, separating Mecklenburg Bay from the Arkona Basin and serving as a bottleneck for water exchange. Located close to the isostatic zero-line for the last 9000 years (Brandes et al. 2025) that separates the rising and subsiding parts of the Baltic Sea, this area holds critical information about past water-level developments and drainage patterns. Previous research has debated whether the Darss Sill served as the drainage threshold for the Ancylus Lake regression around 10.4 cal ka BP, with competing theories proposing either rapid drainage through the Kadet Channel or more gradual outflow through alternative pathways (Björck et al. 2008).

Research cruise EMB306 was conducted from November 22–30, 2022, aboard RV Elisabeth Mann Borgese with the primary objective to locate and investigate preserved fluvial and limnic deposits on the Darss Sill area. The comprehensive survey approach combined high-resolution acoustic mapping techniques with targeted sediment sampling to reconstruct the Holocene paleogeography of the region. The acoustic survey program utilized a Klein 4000 dual-frequency side-scan sonar (100 kHz and 400 kHz) for seafloor mapping, supplemented by parametric sediment echo sounding using an Innomar Medium system with frequencies between 4–15 kHz. Over 120 square kilometers of seafloor were mapped in full coverage, with more than 400 nautical miles of seismic lines

recorded. Geological sampling was conducted using both gravity coring (7-meter steel tube) and vibrocoring (4-meter system) techniques. Twenty-five coring stations were attempted, though not all were successful due to challenging weather conditions and seafloor composition. The recovered sediment cores provided material for sedimentological analysis, grain-size distribution studies, and radiocarbon dating to establish chronological frameworks for the observed stratigraphic sequences.

The acoustic and sedimentological data reveal a complex succession of paleoenvironments preserved in the northeastern Mecklenburg Bay area. Five distinct stratigraphic units were identified, representing different phases of the Baltic Sea's postglacial development. The spatial distribution of Baltic Ice Lake deposits suggests a paleo-coastline at depths of 20–21 meters below present sea level during the initial transgressive phase. Radiocarbon dating of wood fragments and peat yielded ages of 13,788–13,595 cal ka BP. The presence of terrestrial peat deposits and wood remnants indicates proximity to shoreline environments, supporting a connection between Mecklenburg Bay and the southwestern Arkona Basin during the BIL. A widespread post-BIL erosional unconformity was identified, marking a significant regression event. This erosional surface truncates Baltic Ice Lake deposits and represents the onset of lowstand conditions before subsequent water level rise. The Ancyclus Lake highstand is constrained by peat and fine-grained limnic deposits found at water depths of 19 meters below present sea level. Radiocarbon dating of plant material from these deposits yielded ages of 10,765–10,578 cal ka BP and 10,242–10,185 cal ka BP, confirming deposition during the AL transgressive phase. The acoustic data reveal an environment of small, local lakes throughout the Ancyclus Lake stage, persisting until at least 10.2 cal ka BP (close to the postulated AL highstand, indicating little surficial erosion of limnic deposits). A remarkable discovery was the preservation of a northward-draining channel system incised into Ancyclus Lake sediments. Three distinct channel branches were identified, with the western channel averaging 280 meters in width, and the middle and eastern channels each approximately 120 meters wide. The channels exhibit incision depths of 6–7 meters below the surrounding AL deposits, indicating a significant water-level drop following the AL highstand. The geometry and morphology of the incised channel system support a moderate Ancyclus Lake regression rather than catastrophic drainage as suggested by Björck et al. (2008).

The results from EMB306 provide insights into the water-level development of the Darss Sill threshold area in the southwestern Baltic Sea. The indications for moderate rather than catastrophic Ancyclus Lake regression contributes to resolve long-standing debates about the AL drainage patterns. The preserved paleo-landscapes demonstrate the potential for ongoing archaeological investigations in the Baltic Sea region. The identification of former terrestrial surfaces and lake environments at depths of 18–20 meters provides important context for understanding Mesolithic human settlement patterns and mobility in the region.

Analysis so far focused on the southern part of the Darss Sill. Further analysis of the EMB306 data will focus a) on a comparison of the northern and southern entrance of the Cadet channel, crossing the Darss Sill, where several cores of the cruise have not yet been analyzed and b) on the identification of sites with archeological relevance between 10 m and 20 m in side scan sonar data and sediment echo sounder of EMB306 (ongoing as part of a PhD Thesis in the project SUBNORDICA at IOW since 2025).

References

Björck S, A review of the history of the Baltic Sea, 13.0-8.0 ka BP, *Quat. Int.* 1995, 27, 19–40.

Björck S, Andrén T & Jensen, JB, An attempt to resolve the partly conflicting data and ideas on the Ancyclus–Littorina transition, *Pol. Geol. Inst. Spec. Pap.* 2008, 23, 21–26.

Brandes C, Steffen H, Steffen R, Li T & Wu P, Effects of the last quaternary glacial forebulge on vertical land movement, sea-level change, and lithospheric stresses, *Reviews of Geophysics* 2025, 63, e2024RG000852, <https://doi.org/10.1029/2024RG000852>.

Geersen J, et al., A submerged Stone Age hunting architecture from the Western Baltic Sea, *Proc. Natl. Acad. Sci.* 2024, U. S. A. 121, e2312008121.

Scientific Output

List of Publications

Granzow J, Tauber F, Arz HW, Geersen J & Feldens P, Paleogeography of a lake and river system in north-eastern Mecklenburg Bay, southern Baltic Sea, *E&G Quaternary Science Journal* (under review).

Cruise Report

EMB305: https://doi.org/10.48433/cr_emb305

EMB315 and EMB347

Physicochemical characterization of ship emissions in the atmosphere and Baltic Sea water column

Authors

Leibniz-Institute for Baltic Sea Research Warnemünde | Rostock, Germany

H. Osterholz, T. Soares Gonçalves Serafim

University of Rostock | Rostock, Germany

T.M. Gröger, S.K. Piel, R. Zimmermann

Helmholtz Munich | Munich, Germany

T.M. Gröger, S.K. Piel, R. Zimmermann

Charles University | Prague, Czechia

J. Hovorka

Aims of the cruises

The increasing global transport of goods via waterways augments the pressure on marine ecosystems. Large ships disperse, besides gaseous pollutants, huge amounts of particles containing trace metals and organic pollutants into the atmosphere from where they eventually settle and reach the water column. Mitigation strategies mainly focus on the release of sulfur and nitrogen by implementation of Emission Control Areas that currently comprise the Baltic Sea, the North Sea, and most of the U.S. and Canadian coast. Most ships are operated with high-quality fuels or exhaust gas scrubbing systems in these areas, leading to improvements in air quality. However, these improvements only account for specific air pollution parameters with questionable benefits for the environment and health, since emissions from cleaner fuels also entail strong effects. Further, health relevant particles of less than 0.5 μm diameter pass most exhaust gas cleaning systems without significant reduction, even though the mass of particles in the 1–100 μm range is reduced by 80 to 90% (Køcks, Rosenørn et al. 2013). Knowledge gaps concerning ship-derived aerosol deposition to surface seawater and its contribution to marine pollution remain. Especially the ageing processes

during atmospheric transport and in the water column, including UV radiation- or reactive oxygen species-mediated transformations, are not well understood although transformation products can have different effects on biota and their structure dictates their fate in the environment.

The cruises EMB315 (April 2023) and EMB347 (August 2024) were carried out as an integral part of the DFG-funded project PlumeBaSe (Tracing of ship plumes and impact to seawater). The project consortium aims at a detailed, in-situ analysis of the composition of organic aerosols released by the combustion of fossil fuels on ships with focus on the molecular-level transformations of aerosol matter during short- to intermediate term transport in the atmosphere and longer-term residence in the Baltic Sea.

Sampling approach

Cruises EMB315 and EMB347 targeted areas of high ship traffic in the Southwestern Baltic Sea and Pomeranian Bight (Figure 1). Station and underway work were highly dependent on weather conditions and required constant and quick adaptation of the working plan. Our sampling strategy aimed at interlinking atmospheric and water sampling and encompassed a) vessel-mounted systems for physical and chemical characterization of aerosol particles and gas phase as well as high- and low-volume filter sampling; b) mobile online analysis and sampling of aerosols and gas phase via airship and working boat; c) water sampling from different depths via CTD rosette, sea surface microlayer (SML) sampling using the glass plate technique (Wurl and Cunliffe 2014) from the working boat, and monitoring of the ship's continuous seawater intake (Figure 2).

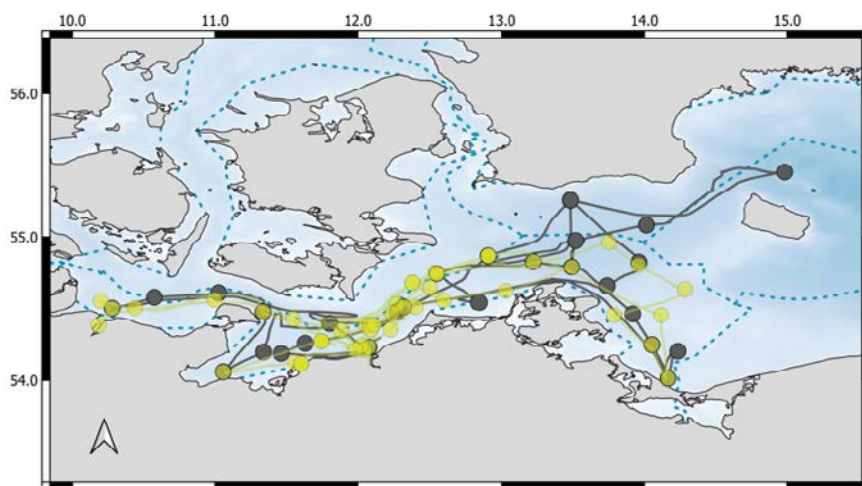


Figure 1: Track chart and stations of EMB315 (yellow) and (gray).

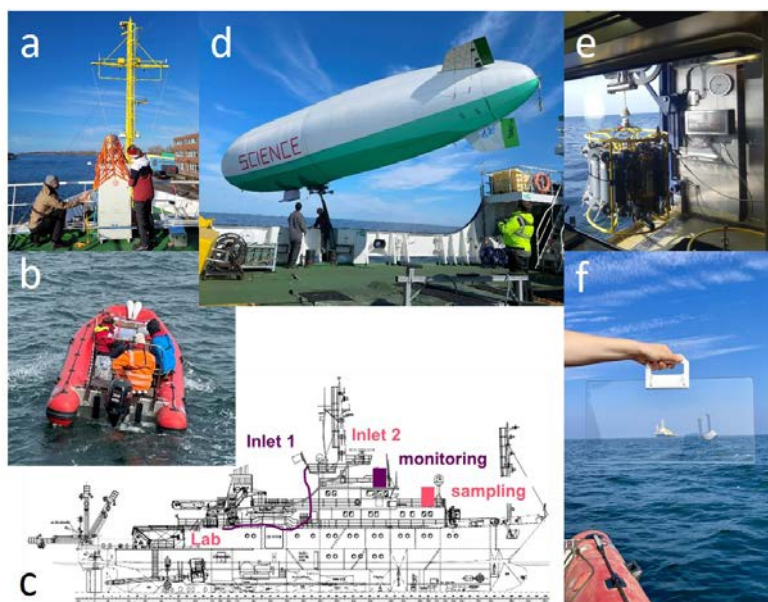


Figure 2: Installation of the high volume aerosol sampler (a), Atmospheric sampler mounted on working boat (b), the EMB measurement setup with inlets for on-/and offline aerosol characterization including SPMS (single particle mass spectrometer), distribution measurements (size mobility particle sizer, SMPS) and low volume sampling setup, monitoring included SMPS and optical particle sizers (c), airship equipped with scanning electrical mobility spectrometer (SEMS, d), and water sampling via CTD rosette (e) plus sea surface microlayer sampling using glass plates (f).

Selected results

Water samples obtained during EMB315 and EMB347 were analyzed with focus on the characterization of the total organic matter pool including dissolved organic carbon (DOC) concentration, dissolved organic matter (DOM) composition via ultrahigh resolution mass spectrometry (FT-ICR-MS) and the thermogenic markers potentially deriving from shipping emissions, Polycyclic Aromatic Hydrocarbons (PAH) and dissolved Black Carbon (dBC) via Benzene Polycarboxylic Acids (BPCA) as outlined in Serafim et al. (2025). During EMB315, wind speeds and wave height were often unfavorable, therefore SML samples could be obtained at 10 stations. While these did not show accumulation of ship aerosol-derived compounds compared to the underlying water sampled at 1 m depth, PAH diagnostic ratios revealed increasing concentrations with increasing contribution from coal combustion, likely residential heating in Poland as indicated by wind back trajectories. In the water column of Pomeranian Bight, the significant influence of terrestrial inputs from the Oder River dominated PAH and dBC signals. In the Arkona Basin, shipping emissions likely played a more important role and specific molecular formulas indicative of organic matter sources as well as anthropogenic pressure from combustion products to the Baltic Sea could be detected.

On a previous test cruise, first single-particle analyses could be successfully demonstrated by the consortium (Rosewig, Schade et al. 2023). PM_{2.5} samples obtained during EMB315 and EMB347 from the Baltic Sea showed elevated PAH concentrations with varying PAH patterns in ship plume samples compared to ambient background samples and primary real world ship emissions were dominated by ultrafine particles, in distinct contrast to the background. Especially these ultrafine particles with a mode < 100 nm, not fully removed by exhaust gas cleaning systems, can exert intense adverse health effects due to their ability to enter the deep lung tissue.

The plumes of individual ships were also examined in more detail by sampling when RV ELISABETH MANN BORGESE remained in the exhaust plume of a ship travelling ahead and upwind in order to collect sufficient material for the chemical characterization of the gas and particle phases, and to perform artificial ageing experiments of ship aerosols (during EMB347) via an Oxidation Flow Reactor (OFR). An OFR enables the simulation of multiple days of atmospheric photochemical aging through exposure of the sample to OH radicals. By this means, an insight into plume behavior over a prolonged time can be gained which is usually not accessible due to dilution. Figure 3 shows preliminary data of the particle size distributions of fresh and aged marine background and a ship plume. The formation of secondary organic aerosol (SOA) by nucleation can be hypothesized by the generation of small particles (<20nm) in the aged compared to the fresh sample. The contribution of aged ship plumes to air pollution is therefore likely, while it was previously deemed neglectable (Ausmeel et al. 2019).

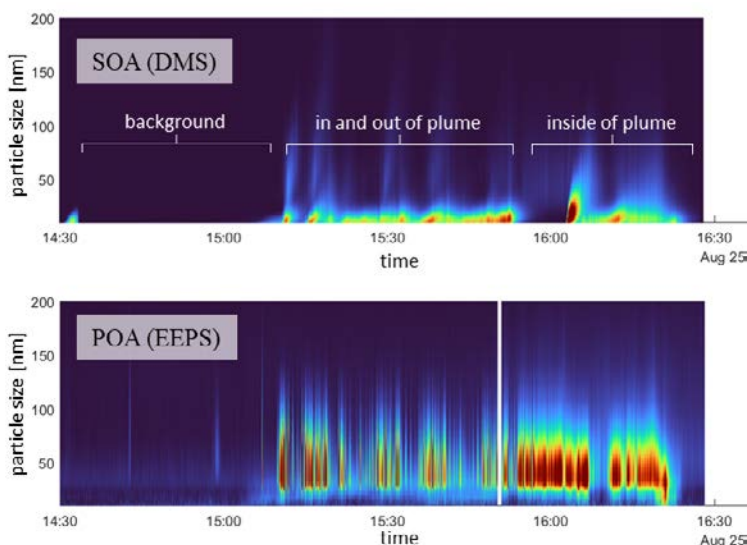


Figure 3: Particle size distribution of fresh (top) and OFR-aged (bottom) sampling showing background and plume behavior (unpublished data).

Another goal of EMB315 and EMB347 was to resolve in situ plume dynamics via online measurements and filter sampling using an airship, which offered the needed payload to transport instruments and samplers directly into the ship plumes with minimal disturbance. Due to the challenge of high wind speeds, the airship could not be used as often as intended. Nonetheless, several flights could be conducted and ship plumes at a height about 70 m above the sea surface could be measured at distances approximately 100–150 m from the ships. The plumes were characterized by particle number concentrations above 105 cm^{-3} for the size range of 5–350 nm. In-plume numbers size distributions were monomodal at the count mean diameter of 65 or 120 nm, indicating if measured ships were equipped with exhaust gas cleaning systems.

During EMB347 in August of 2024, the seawater was frequently colder than the air in the marine atmospheric boundary layer (MABL). As a result, frequent temperature inversion within the MABL was expected, in contrast to cruise EMB315 in March 2023. During EMB347, close to the Swedish coast, we observed a thinning of the inversion layer from ~100 m to approximately 30 m above sea level within 6 hours. Since the emission height of ship stacks ranges between ~10–30 m, ship emission pollutants accumulate in the rather thin MABL in close proximity to the sea level. The prolonged contact of the increased pollutant concentrations with the Baltic Sea can then entail large environmental impacts. Water chemistry analyses from this event are ongoing, but initial results showed enriched concentrations of dBC in the underlying water compared to deep water, previously not observed during EMB315.

Further, aerosol measurements near the sea surface conducted behind moving ships using a working boat revealed faster-than-dilution nanoparticle decrease in proximity to followed ships. The hypothesized mechanisms of scavenging of small (~20 nm) particles by seawater droplets could explain low nanoparticle counts at higher heights, and provide a significant and fast transport mechanism of ship aerosols to the water column, with major environmental consequences, warranting further exploration.

Acknowledgements

We thank the captain and crew of RV ELISABETH MANN BORGESE for their immense efforts and support during the cruise. Additional support was provided through Prof. Dr. T. Adam and Dr. J. Schade. The research was funded by the Deutsche Forschungsgemeinschaft (DFG – 471841824) and the Czech Science Foundation (GACR, 22-03426L) within the bilateral research project “PlumeBaSe”.

References

Ausmeel S, Eriksson A, Ahlberg E & Kristensson A, Methods for identifying aged ship plumes and estimating contribution to aerosol exposure downwind of shipping lanes, *Atmospheric Measurement Techniques* 2019, 12, 4479–4493, doi:10.5194/amt-12-4479-2019.

Køcks M, Rosenørn T, Butcher A, Mølgaard S, Hansen JP, Fuglsang K & Bilde M, Shipboard characterization of a wet scrubber system during operation (part II): Influence on particle number concentration, particle size distribution and chemical composition, *ETH-Conference on Combustion Generated Nanoparticles (Zurich)* 2013.

Rosewig EI, Schade J, Passig J, Osterholz H, Irsig R, Smok D, Gawlitta N, Schnelle-Kreis J, Hovorka J, Schulz-Bull D, Zimmermann R & Adam TW, Remote Detection of Different Marine Fuels in Exhaust Plumes by Onboard Measurements in the Baltic Sea Using Single-Particle Mass Spectrometry, *Atmosphere* 2023, 14, doi:10.3390/atmos14050849.

Cunliffe M & O Wurl, Guide to best practices to study the ocean's surface, Occasional Publications of the Marine Biological Association of the United Kingdom, Plymouth, UK 2014, 118 pp.

Scientific Output

List of Publications

Serafim TSG, Schulz-Bull DE, Rüger CP, Dittmar T, Niggemann J, Zimmermann R, Waniek JJ & Osterholz H, Imprint of incomplete combustion processes on the water column of the anthropogenic-pressured Baltic Sea, *Science of the Total Environment* 2025, 964, 178537, doi:10.1016/j.scitotenv.2025.178537.

Piel S, Gröger T, Czech H, Hovorka J, Osterholz H, Adam H & Zimmermann R, Aging Independent Ship Emissions on the Baltic Sea using an OFR, in preparation.

List of conference presentations

2025 | **Chemical and Physical Characterization of Ship Emissions – Taking the Step from Lab to Real-World Ship Emissions** ANAKON, Leipzig, Germany.

2025 | Tracing the Products of Combustion Processes in the Baltic Sea Water Column EGU European Geosciences Union General Assembly, Vienna, Austria.

2024 | The Assessment of the Chemical and Physical Properties of Ship Exhaust – Investigating the Fate of Ship Plumes in the Baltic Sea (PlumeBaSe) ANALYTICA, Munich, Germany.

2024 | Chemical Characterization of Photochemical Aging of Ship Particulate Matter Emissions – Determination of Marker Compounds and PAH Decay Rates AAAR American Association for Aerosol Research, Albuquerque, USA.

2024 | Comparison of the emission characteristics of land-based engine test benches with open water real ship emissions – Technical realization and physico-chemical findings EAC European Aerosol Conference, Tampere, Finland.

2024 | Distribution of pyrogenic organic matter in the southwestern Baltic Sea Baltic Earth Conference, Jurmala, Latvia.

2024 | Airborne Detection of Aerosol Particle Size Distributions in Marine Atmospheric Boundary Layer at Baltic Sea CAS Annual Conference of the Czech Aerosol Society, Milovy, Czechia.

2024 | Measurement of Vertical Profile for Temperature and Relative Humidity in the Atmospheric Boundary Layer Using a Drone CAS Annual Conference of the Czech Aerosol Society, Milovy, Czechia.

2024 | Size Distribution and Number of Droplets Generated by Sailing Ships CAS Annual Conference of the Czech Aerosol Society, Milovy, Czechia.

2023 | Shipboard Size Distributions Measurements and Sampling of Aerosol Particles in Ship Plumes at Baltic Sea AAAR American Association for Aerosol Research, Portland, USA.

2023 | Airborne and Shipboard Measurements of Aerosol Particle Size Distributions in Ship Plumes at Baltic Sea AAAR American Association for Aerosol Research, Portland, USA.

2023 | Aerosol Particle Size Distributions in Ship Plumes at Baltic Sea by Airship and Working Boat Measurements CAS Annual Conference of the Czech Aerosol Society, Čeladná, Czechia.

Data

All physical oceanographic can be investigated and downloaded at:
IOWDB – the oceanographic database of the institute
<https://odin2.io-warnemuende.de/#/>

Cruise Reports

EMB315: https://doi.org/10.48433/cr_emb315

EMB347: https://doi.org/10.48433/cr_emb347

EMB320

Assessing the impact of mobile bottom trawl fishing in marine protected areas (Natura 2000) of the western Baltic Sea, and investigations of bacterioplankton along the salinity gradient of the Baltic Sea (“MGF-Salinity”)

Authors

Leibniz Institute for Baltic Sea Research | Warnemünde, Germany

K. Jürgens, J. Piontek, M. Gogina, I. Schulze

Biology Centre of the Czech Academy of Sciences | Ceske Budejovice, Czechia

M. Salcher, M. Haber, P. Layoun, C. Fernandes

University of Cologne | Cologne, Germany

H. Arndt

GFZ Helmholtz Centre for Geosciences | Potsdam, Germany

S. Bernsee, S. Okolski, J. Kallmeyer

Introduction & objectives

Two research projects were carried out during the expedition EMB320 with RV ELISABETH MANN BORGESE (16.06.–03.07.2023): (1) Investigation of the expected impact of the exclusion of mobile, bottom-touching fisheries in marine protected areas (MPAs) of the Baltic Sea (DAM pilot mission “MGF-Baltic Sea II”). A consortium of scientists from Leibniz, Helmholtz, Thünen and university institutes is investigating how the benthic ecosystems of the Natura 2000 areas in the German Exclusive Economic Zone (EEZ) of the Baltic Sea will develop after the exclusion of mobile bottom-touching fisheries. The proposed cruise serves to record all components of the benthic food web, from prokaryotes to macrozoobenthos, sediment characteristics and biogeochemical processes in the protected areas

Fehmarnbelt, Rönnebank and Odra Bank. This expedition served to complement previous research cruises within this project, by assessing the early summer situation for 2023 in the investigation areas. As in previous cruises, comparative areas inside and outside the MPAs were sampled. (2) A research project, funded by the Czech Science Foundation, aims to better understand the adaptations of microorganisms along the salinity gradient of the Baltic Sea. One focus is on the bacterial cluster “SAR11”, which can dominate in marine, brackish and freshwater systems. The strong salinity gradient of the Baltic Sea (oligohaline – mesohaline – marine) leads to distinct shifts in the microbial community with a stable population of brackish water SAR11 and other endemic microbes in the main basins. Marine and freshwater bacteria, on the other hand, coexist with brackish water species in coastal and marine regions. High-throughput cultivation and hybrid metagenomics will be used to obtain genomes for phylogenomic analyses, which are used to analyse evolutionary salinity adaptations.

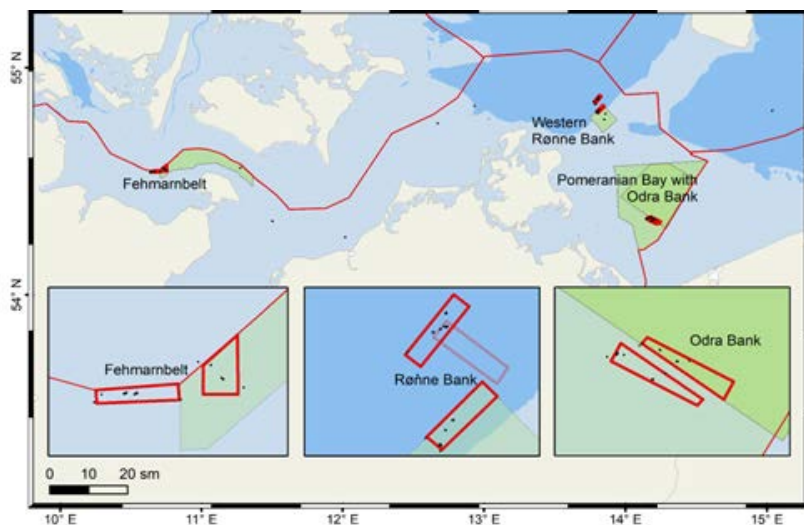


Figure 1: Overview map with sampling areas inside and outside of the MPAs Fehmarnbelt, Rönnebank and Odra Bank, and sampled locations in the south-western Baltic Sea.

The main working areas of EMB320 cruise were for research project (1) the MPAs Odra Bank and Rönnebank in the Pommeranian Bay of the Southern Baltic Sea, and Fehmarnbelt in the Western Baltic Sea. For these MPAs, investigation areas have been identified previously and are within or outside (reference) of the MPAs (Figure 1). For all areas, specific sampling locations have been determined and sampled in previous cruises 2020–2022. Sampling during EMB320 cruise was conducted with a similar methodology as previously.

Additionally, for research project (2), the salinity gradient of nearly the whole Baltic Sea was sampled for the water column, from the Kattegat in the

Northwestern Baltic Sea until the entrance of the Gulf of Finland in the Northeast (Figure 2).

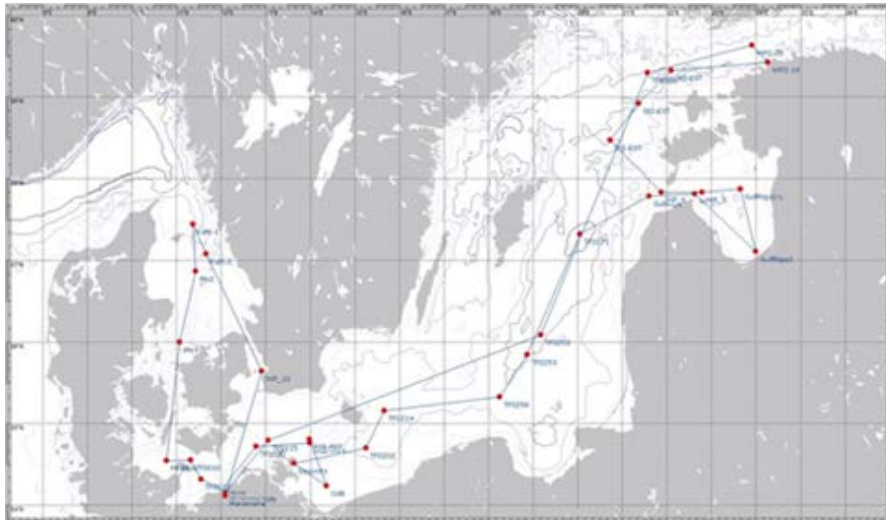


Figure 2: Overview map of cruise track and sampling stations for assessing the salinity gradient of the Baltic Sea during cruise EMB320.

A) MGF Baltic Sea Project

The EMB320 cruise was part of the time series for assessing the biodiversity and sediment functions of the MPAs within the German EEZ (Fehmarnbelt, Rönnebank, Odra Bank). Compared to previous MGF cruises only a reduced sampling program was conducted as the proposed exclusion of bottom trawling had not been achieved yet, and the principal baseline before exclusion was already assessed in previous cruises. Therefore, the focus was on some key benthic components for the time series analyses, and on the hitherto undersampled area Rönnebank.

Prokaryotes and microbial activities (J. Piontek, K. Jürgens; IOW; S. Bernsee, J. Kallmeyer, GFZ) – The main objective of the microbiological working group within the MGF project is to investigate the impact of bottom trawling on the composition and functioning of prokaryotic communities in the sediments of the MPAs, and, for comparison, in the nearby reference areas. Prokaryotic cell numbers, heterotrophic activity, taxonomic composition and the inventory and expression of functional genes in sediment samples from the surface to 15–20 cmbsf were analyzed. Total prokaryotic abundances were quantified by fluorescence microscopy using a DNA-binding dye. On-board incubations were conducted to estimate rates of extracellular aminopeptidase activity and heterotrophic bacterial biomass production. The taxonomic community composition was analyzed by 16S rRNA high-throughput sequencing. The analysis of gene abundances and gene expression focused on metabolic processes that

are important for ecosystem services including carbon remineralization, inorganic nutrient release, and sulfur cycling at the sediment-water interface. Preliminary results show similar levels of heterotrophic bacterial biomass production in surface sediments of the three MPAs and the respective reference areas outside. Leucine uptake rates corresponded to secondary production of $0.18 \pm 0.04 \mu\text{g C cm}^{-3} \text{ h}^{-1}$ in Fehmarn Belt surface sediments, $0.17 \pm 0.05 \mu\text{g C cm}^{-3} \text{ h}^{-1}$ in Odra Bank surface sediments and $0.14 \pm 0.02 \mu\text{g C cm}^{-3} \text{ h}^{-1}$ in Rønne Bank surface sediments. The rates are similar to those determined in previous years during summer.

Benthic sulfate reduction rates were measured via radiotracers in triplicates in sediments retrieved by the MUC. Microbial sulfate reduction represents the most dominant anaerobic organic carbon degradation pathway in marine sediments, and the quantity and vertical pattern in this microbial process might constitute an important indicator for sediment disturbance due to bottom trawling.

Nano- and Microfauna (M. Sachs, H. Arndt; University of Cologne) – Protists in the size range of 1–20 μm (nanofauna) and in the size range of 20–200 μm (microfauna) are essential parts of the benthic food web as they channel bacterial production to higher trophic levels (meiofauna, macrozoobenthos), which in turn act as nutritional basis for demersal fish. The bacterial abundance and production is assumed to be regulated by the predation pressure of the nano- and microfauna. Thereby also a variety of geochemical processes mediated by bacteria should be influenced by protists. During cruise EMB320, a combination of molecular work, fixed samples, live-counting of more delicate protists, and culturing approaches was used to assess the abundance and composition of the protist communities. Highest abundances of heterotrophic protists were always revealed from the upper surface layer of sediment (0–1 cm). Abundances in the Rönnebank area were higher than at those obtained in the former year from Fehmarnbelt (AL570) and comparable to those obtained in the previous years from studies at Odra Bank (EMB 267). In contrast to studies from the Odra Bank, protists were not found at sediment depths below 4 cm depth. Dominating groups of nanofauna were kinetoplastids (neobodonids), euglenids, less important were colourless dinoflagellates, bicosoecids, colourless cryptomonads, ancyromonads, amastigomonads, cercomonads, and thaumatomonads. Among microfauna, ciliates dominated the sediment samples with representatives of predatory litostomatids and several bacterivorous spirotrichs and scuticociliates.

Macrozoobenthos (M. Gogina, IOW) – One focus was the MPA Rönnebank which could not be adequately sampled in previous MGF-cruises. Based on the first visual estimate of taxonomic composition in the Rönnebank (RB) area, among species dominating the abundance and biomass were the mollusc *Macoma balthica*, the priapulid worm *Halicryptus spinulosus*, few polychaetes such as *Scoloplos armiger*, *Capitella capitata*, *Alitta succinea* and the lugworm *Arenicola marina*. The bioturbation traces of *A. marina* were commonly observed on

underwater videos. Generally, with the exception of one station, the sediment was similar at all MPA and REF stations visited. Another preliminary observation is that with higher distance from MPA and riff, substantially less alive individuals of *M. balthica* were on average collected per grab sample at REF stations. Following HELCOM HUB, the habitat at RB can be classified as “AB.H3L1 Baltic aphotic muddy sediment dominated by Baltic tellin (*M. balthica*)”.

Similar to previous years, at the MGF stations of sandy Odra Bank area the bivalves *Mya arenaria* (deep burrowing suspension feeder), *Macoma balthica* (surface deposit feeder), and *Cerastoderma glaucum* (shallowly burrowing suspension feeder), as well as polychaete *Hediste diversicolor* (an active burrowing sediment reworking generalist) were most frequently observed species in macrobenthic grab samples. In the dredge, that was too light to penetrate much into sand, demersal organisms such as common shrimp *Crangon crangon* often found buried into the surface sediment, mysids, as well as epibenthic suspension feeding bivalve *Mytilus edulis* (blue mussel) were found. Samples obtained at Odra Bank stations were typical for HELCOM ‘HUB’ “Underwater Biotope AA.J3L9 ‘Baltic photic sand dominated by multiple infaunal bivalve species”.

As in previous sampling campaigns, in muddy Fehmarnbelt areas the diversity was high, and biomass obviously dominated by *A. islandica*, and other bivalves like *Abra alba*, polychaetes like *Nephtys ciliata* and *Terebellides stroemii*, echinoderms *Ophiura albida* and *Asterias rubens*, and the cumacean *Diastylis rathkei*.

B) Microorganisms along the salinity gradient of the Baltic Sea

The main goal was to sample the complete salinity gradient of the Baltic Sea with several oligohaline stations in the Gulf of Riga and the Gulf of Finland (approx. 5 PSU), brackish stations in the Eastern Gotland Basin, Northern and Southern Baltic Proper (7–8 PSU) intermedia brackish-marine stations in the Kattegat (25–30 PSU) and marine stations at the Skagerrak (30–35 PSU). Unfortunately, bad weather conditions with an upcoming storm prevented sampling of the marine stations at the Skagerrak. One focus was to track transitions along the saline-freshwater border in the composition and evolutionary history of aquatic microbes, with a special emphasis on the SAR11 group. Samples taken from 5 m depths were analyzed in detail (Figure 3) as these were used for high-throughput dilution-to-extinction cultivation and metagenomic sequencing. Highest prokaryotic abundances (up to 4×10^6 cells ml⁻¹) were recorded in the Gulf of Riga and the main basin of the Baltic Sea. Lowest densities were found at stations with highest salinities (Kattegat) and below 50 m in the Central Baltic proper.

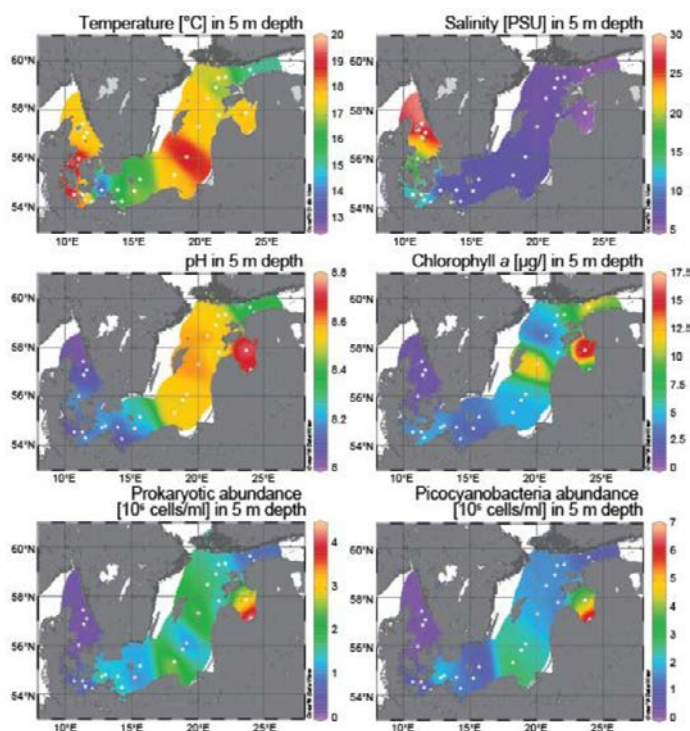


Figure 3: Water temperature, salinity, pH, chlorophyll a, total prokaryotic and picocyanobacterial abundance in 5 m water depth at the stations sampled during the EMB320 cruise.

A total of 26 metagenomic samples were sequenced with Illumina NovaSeq 6000, resulting in 618.9 Gb data. This resulted in 1490 metagenome-assembled genomes (MAGs) with completeness >50% and <5% contamination (Figure 4), on average 57 per sample. More than one third (36.7%) of the assembled MAGs were of high quality (>90% completeness, <5% contamination), and another 44% were of medium-high quality (>70% completeness, <5% contamination) (Figure 4b). The majority of MAGs were affiliated with Pseudomonadota (42.1%), Actinomycetota (24.4%) and Bacteroidota (20.1%), and to a lesser extent with Verrucomicrobiota (6.2%), and Cyanobacteriota (4.4%) (Figure 3c, Figure 4). Clear differences could be observed for MAGs obtained from oligohaline, brackish and marine conditions, with the isolation source matching closely to observed maximal abundances, as determined with metagenomic fragment recruitment. For example, the SAR11-IIIa genus IMCC9063 was the most abundant genus in the complete dataset, with maxima in oligo- and mesohaline conditions and decreasing trend towards higher salinities. In contrast, the SAR11-I genus *Pelagibacter* was less abundant and prevailed mainly at higher salinities. Both taxa, however, contained multiple species with unique species-specific distribution patterns. Two additional SAR11 genera (SYDM01 and CACCCN01) were either restricted to oligohaline conditions or had maxima at salinities of 12 PSU, while the freshwater genus *Fontibacterium*

was only marginally present at very low salinities. Similarly, many genera of Nanopelagicales (Actinomycetota), Planctomycetota, and Burkholderiales (Pseudomonadota) were clearly restricted to low salinities (up to 6–8 PSU), and representatives of several phyla were only assembled from low-salinity samples (Gemmatimonadota, Chloroflexota). The brackish Baltic Proper (salinities 6–8 PSU) was – besides SAR11-IIIa – mainly inhabited by uncultivated Pseudohongiellaceae, SAR86 (Pseudomonadota), uncultivated Coraliomargaritaceae (Verrucomicrobiota), Cyanobiaceae (Cyanobacteriota), specific genera of Flavobacteriales (Bacteroidota), and brackish Methylophilaceae (Pseudomonadota). Several taxa were restricted to higher salinities (28–30 PSU), such as Poseidoniaceae (Thermoplasmatota, Archaea) and specific genera of Flavobacteriales (Bacteroidota), Rhodobacteraceae, and Parvibaculales (Pseudomonadota). Only one uncultivated species of Pseudohongiellaceae was detected in all samples ($>0.5 \times$ coverage per Gb, $>40\%$ breadth), however, with lower abundances at high salinities.

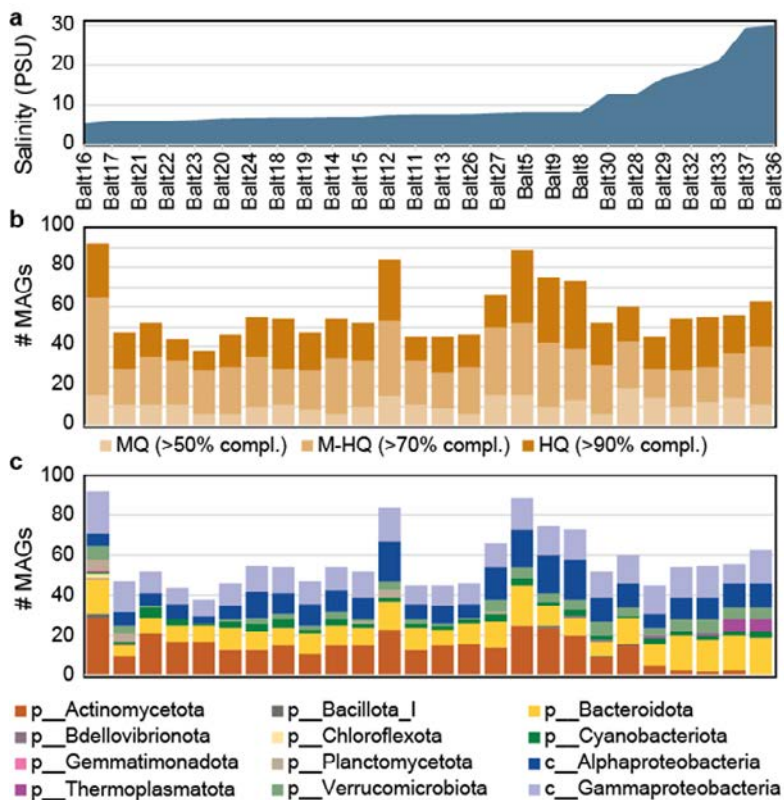


Figure 4: Overview of metagenome-assembled genomes (MAGs) per sample. **a:** Salinities at the different sampling stations, samples are sorted from low to high PSU in panels b and c. **b:** Number of MAGs per sample; MQ: medium quality MAGs ($>50\%$ completeness, $<5\%$ contamination); M-HQ: medium to high quality MAGs (70–89% completeness, $<5\%$ contamination); HQ: high quality MAGs ($>90\%$ completeness, $<5\%$ contamination). **c:** Taxonomy of MAGs per sample. Taxonomy was assigned with GTDB.

To isolate new strains of oligo- and mesohaline prokaryotes, a total of 67 96-well plates containing artificial media with different salinities were inoculated during the cruise. These were screened for cultures by flow cytometry after 6 weeks of incubation at 16°C. We obtained a total of 594 initial cultures (cultivation efficiency 9.23%, Figure 5a). Of these, 20-24% each were either mixed cultures as assessed by 16S rRNA sequencing, showed growth arrest before 16S rRNA PCR could be conducted, or still lack PCR screening results. So far, 185 strains have been identified as axenic and taxonomy was assigned.

Planned and ongoing bioinformatic studies with the metagenomic-assembled genomes, together with physiological and experimental studies with the cultured representatives, aim to better understand the distribution and functional potential of prokaryotes along the Baltic salinity gradient, and their metabolic adaptations to different (and fluctuating) salinities.

Acknowledgements

This cruise was approved by the “Gutachterpanel Forschungsschiffe” of the German Research Foundation under license no. GPF 23-2/031.

We highly appreciate the financial support from BMBF, which was granted to IOW under the ID 03F0937A to conduct the project “DAM Schutz und Nutzen: MGF Ostsee – Ausschluss mobiler grundberührender Fischerei in marinen Schutzgebieten der Ostsee; Leitantrag; Vorhaben: Entwicklungsszenarien benthischer Lebensgemeinschaften und Sedimentfunktionen”, and to realise cruise EMB320.

Scientific Output

List of Publications

Gogina M, Kröncke I, Marx D, & Zettler ML, Status und Trends der biologischen Vielfalt an Küsten und in Küstengewässern, Zoobenthos, In Wirth C, Bruelheide H, Farwig N, Marx JM & Settele J (Hrsg.), Faktencheck Artenvielfalt: Bestandsaufnahme und Perspektiven für den Erhalt der biologischen Vielfalt in Deutschland 2024, 681–684, München: oekom., doi.org/10.14512/9783987263361.

Piontek J, Schott T, Roeser P, Kallmeyer J, et al., A novel lineage of *Thermodesulfovibrio* contributes to sulfate reduction in sandy sediments of the southern Baltic Sea, (ISME communications, in review).

Sachs M, Nitsche F & Arndt H, Cryptic cryptomonads – revision of the genus *Goniomonas*, J Eukaryot Microbiol 2025, doi.org/10.1111/jeu.70038.

Schönke M, Schulze I, Gogina M, von Dorrien C, et al., What AIS Misses and Acoustics Reveal: Monitoring Seafloor Disturbance and Recovery from Bottom Trawling in the Southern Baltic Sea Over Five Years, doi.org/10.2139/ssrn.5381183 (Ecological Informatics, in review).

List of conference presentations

2024 | **Revealing the evolution of trawling activity in the Fehmarn Belt.** GeoHab Conference 2024, Arendal, Norway.

2024 | **Examining the biogeochemical footprint of bottom-trawling in Baltic Sea sediments.** MGF Seminar 2024, Warnemünde, Germany.

2024 | **Macrozoobenthos.** Status seminar MGF-Ostsee & MGF-Nordsee Annual meeting 2024, IOW, Warnemünde, Germany.

2024 | **A phylogenetic revision of the widely distributed heterotrophic flagellate *Rhynchomonas nasuta*.** International Meeting of the German Society of Protozoology, Haltern am See, Germany.

2023 | **WP 3.2 Macrozoobenthos: Effects of bottom trawl fishing and its exclusion on benthic macrofauna communities and key species in MPAs of the western Baltic Sea.** MGF Nordsee MGF Ostsee Final Meeting and Kickoff, Bremerhaven, Germany, 25.04.2023.

2023 | **The effects of bottom-trawling on early diagenesis in the Baltic Sea.** Baltic Sea Science Congress (BSSC 2023), Helsinki, Finland

Data

Prokaryotes:
<https://doi.org/10.1594/PANGAEA.961796>

Benthic biology:
MGF-DAM project repository, IOW

Macrozoobenthos variables:

IOW database and repository (contact person: Dr. Mayya Gogina)

Multibeam echosounder data:

IOW database and repository (contact person: Dr. Peter Feldens)

Cruise Report

EMB320: in review, will be added

EMB324

Dynamics of redox-sensitive trace metals and biomarkers in the salinity gradient of the Baltic Sea

Authors

Leibniz Institute for Baltic Sea Research Warnemünde | Warnemünde, Germany

O. Dellwig, A. Wegwerth, J. Kaiser

University of Cologne | Cologne, Germany

R. Yang, C. Münker

ETH Zürich | Zürich, Switzerland

M. Sun, D. Vance

Christian-Albrechts-University Kiel | Kiel, Germany

F. Elling

Technical University of Denmark | Roskilde, Denmark

J. Qiao

Aim of cruise EMB324

Cruise EMB324, which was carried out between 19. August and 7. September 2023, followed the entire salinity gradient of the Baltic Sea with a near-ocean situation in the Skagerrak and almost freshwater conditions in the most northern part of the Bothnian Bay. In addition to 28 transit stations (surface and bottom water sampling), 9 main stations (water column, sediment and porewater sampling) located in the Skagerrak (SK1-new), Arkona Basin (AB), Bornholm Basin (BoB), Gdansk Basin (GdB), Gotland Basin (GB1), Gulf of Finland (GF1), Bothnian Bay (BB), Bothnian Sea (BS) and Norrköpping Deep (ND) were sampled. During the cruise, the chosen main stations covered redox settings ranging from oxic (SK1-new, AB, BB, BS) to hypoxic (GF1) and even euxinic (BoB, GdB, GB1, ND) conditions in the deeper water column.

The major goals of cruise EMB324 addressed three topics covering inorganic, organic and environmental (bio)geochemistry: First, a better understanding of

the processes controlling the abundance and isotopic composition of tungsten (W) to test its applicability as a paleo-redox proxy for the deeper basins of the Baltic Sea. Second, testing and validation of the robustness of biomarker proxies for sea surface salinity/temperature and cyanobacterial biomass reconstructions. Third, testing whether particle-reactive ^{234}Th can be used to track microplastics dynamics in the water column. While first W and biomarker data are available yet, the microplastic approach still remains at a methodological stage. In addition to the original goals, the trace metal program has been expanded by sampling for dissolved thallium (Tl) and nickel (Ni) isotopes, which both also represent promising redox proxies.

Oceanographic situation in the Baltic Sea during cruise EMB324

The salinity distribution along the cruise track revealed typical vertical and lateral gradients ranging from 32.0–35.2 and 2.0–3.4 in the surface and bottom waters at stations SK1-new in the Skagerrak and BB in the Bothnian Bay, respectively. While bottom waters were still oxygenated at stations SK1-new, AB, BS and BB, the water body was hypoxic below ~80 m water depth at station GF1. A first appearance of sulfide was detected in the bottom waters at the seasonally hypoxic stations BoB (7.5 μM) and GdB (48 μM). Most striking was, however, the absence/presence of oxygen/sulfide below ~70 m water depth at the main stations GB1 and ND, which suggests along with adjoining transit stations a huge extension of euxinic waters in the central Baltic Sea. Though seemingly paradox, this development is most likely related to the latest Major Baltic Inflow, which reached the central Gotland basin around February 2015 (Dellwig et al., 2018). Although the waters from the North Sea oxygenated the formerly euxinic water body of the Gotland Basin, this effect had only a short duration of a few months (Dellwig et al., 2018, 2021). More important appears, however, the huge salt content of these intruding waters, which still forms a dense water body preventing vertical water column mixing and ventilation in the eastern Gotland Basin thereby fostering the rapid re-establishment of euxinic waters.

Behavior of tungsten under differing redox settings

The group 6 transition metal W and its isotopes have been recently suggested as a new promising redox proxy (Dellwig et al., 2019; Kurzweil et al., 2022; Roué et al., 2021; Yang et al., 2022). However, the behavior of W in the marine/brackish environment is poorly understood so far, especially with respect to different redox scenarios. While W is assumed to behave conservatively in form of the tungstate oxyanion in the oxygenated ocean with a concentration around 10 ng/L, magnitudes higher W concentrations have been reported for euxinic settings due

to an increased solubility triggered by thiolation (Sohrin et al., 1987, Mohajerin et al., 2016; Dellwig et al., 2019).

Preliminary measurements of dissolved W and Mn in the water column and porewaters at the main stations are shown in Figure 1. While comparatively uniform profiles and low concentrations of W characterized the oxygenated waters of all main stations, increased W levels were found in the hypoxic/euxinic water bodies of stations GF1, BoB, GdB, ND and GB1 (Figure 1a). Despite a relatively low bottom water column sulfide level, concentrations of dissolved W were highest and nearly reached 250 ng/L at station BoB. In contrast, dissolved W only slightly exceeded 100 ng/L at the most euxinic station GB1. Noteworthy is also the higher dissolved W level in the hypoxic but still oxygen-containing bottom waters of station GF1, which also showed highest concentrations of dissolved Mn and W in the euxinic porewaters (Figure 1b). On the other hand, dissolved W was relatively low in both the Mn-rich porewaters of station BB and sulfide-rich porewaters of station AB. These preliminary findings suggest that in addition to sulfide, knowledge of further environmental parameters such as porewater W fluxes, the basin geometry and in particular sedimentary sources and sinks of W appear essential for understanding the obviously more complex behavior of W under differing redox scenarios.

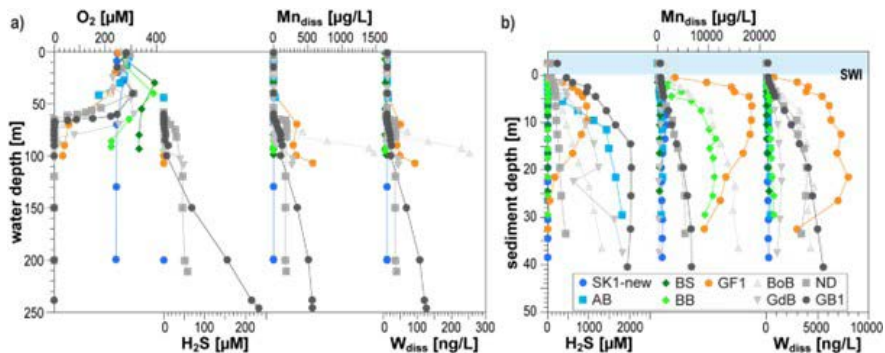


Figure 1: Concentrations of oxygen (O₂, only water column), total sulfide (H₂S), dissolved Mn and dissolved W in the a) water column and b) porewaters of the main stations in the Baltic Sea during cruise EMB324.

First W isotope data from sites GB1 and BB revealed clear differences between the two sites. At the GB1 site, sediments and porewaters were characterized by elevated W abundances and a progressive increase in $\delta^{186/184}\text{W}$ values with depth. In contrast, sediments deposited under oxic conditions at station BB showed lower W contents, with heavier surface $\delta^{186/184}\text{W}$ values that decrease downcore. In both cores, porewater W concentrations increase with depth, but absolute values are considerably higher at station GB1. Porewaters from station BB display $\delta^{186/184}\text{W}$ values comparable to or slightly lighter than the overlying water column,

whereas $\delta^{186/184}\text{W}$ values in euxinic porewaters were significantly lighter relative to the water column.

These findings demonstrate that W isotopes in sediments and porewaters respond in distinct ways to Mn and S cycling under varying redox regimes. Overall, these data provide new insights into W isotope behavior and underscore the potential of $\delta^{186/184}\text{W}$ as a paleo-redox proxy.

Biomarkers as a potential proxy for surface seawater salinity

First results of the analyses of suspended particulate matter in surface water samples (~400 L water volume), reveal a relationship between the percentage of the C_{37:4} alkenone and sea surface salinity along the salinity gradient between the Skagerrak and the Bothnian Bay as well as for the south-central Baltic Sea (Figure 2). Such relation suggests that C_{37:4} potentially represents a promising proxy to estimate past salinity changes in surface waters documented in Baltic Sea sediments. The future plans will comprise the distribution of different lipid biomarkers in the surface water and recent sediments in order to improve/develop molecular proxies for salinity, temperature and primary production.

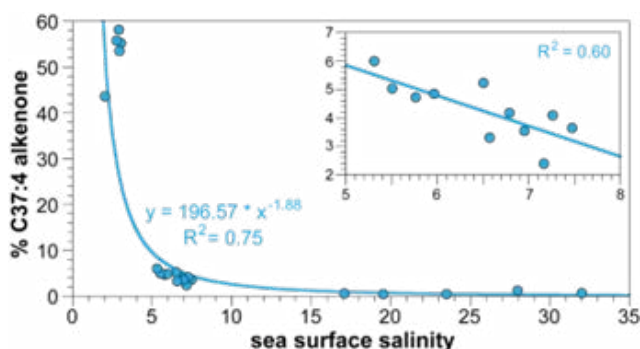


Figure 2: Percentage of the C_{37:4} alkenone in the surface water of the Baltic Sea as a function of sea surface salinity. The inserted graph represents data from the south-central Baltic Sea only.

References

Dellwig O, Schnetger B, Meyer D, Pollehne F, et al., Impact of the Major Baltic Inflow in 2014 on Manganese Cycling in the Gotland Deep (Baltic Sea), *Frontiers in Marine Science* 2018, 5, doi: 10.3389/fmars.2018.00248.

Dellwig O, Wegwerth A & Arz HW, Anatomy of the Major Baltic Inflow in 2014: Impact of manganese and iron shuttling on phosphorus and trace metals in the Gotland Basin, Baltic Sea, *Continental Shelf Research* 2021, 223, 104449, doi: 10.1016/j.csr.2021.104449.

Dellwig O, Wegwerth A, Schnetger B, Schulz H, et al., Dissimilar behaviors of the geochemical twins W and Mo in hypoxic-euxinic marine basins, *Earth-Science Reviews* 2019, 193, 1–23, doi: 10.1016/j.earscirev.2019.03.017.

Kurzweil F, Dellwig O, Wille M, Schoenberg R, et al., The stable tungsten isotope composition of sapropels and manganese-rich sediments from the Baltic Sea, *Earth and Planetary Science Letters* 2022, 578, 117303, doi: 10.1016/j.epsl.2021.117303.

Roué L, Kurzweil F, Wille M, Wegwerth A, et al., Stable W and Mo isotopic evidence for increasing redox-potentials from the Paleoproterozoic towards the Paleoproterozoic deep ocean, *Geochimica et Cosmochimica Acta* 2021, 309, 366–387, doi: 10.1016/j.gca.2021.05.013.

Yang R, Li T., Stubbs D, Chen T, et al., Stable tungsten isotope systematics on the Earth's surface, *Geochimica et Cosmochimica Acta* 2022, 322, 227–243, doi: 10.1016/j.gca.2022.01.006.

Mohajerin TJ, Helz GR & Johannesson KH, Tungsten–molybdenum fractionation in estuarine environments, *Geochimica et Cosmochimica Acta* 2016, 177, 105–119, doi: 10.1016/j.gca.2015.12.030.

Sohrin Y, Isshiki K, Kuwamoto T & Nakayama E, Tungsten in north pacific waters, *Marine Chemistry* 1987, 22, 95–103, doi: 10.1016/0304-4203(87)90051-X.

Scientific Output

List of Publications

Not applicable yet.

List of conference presentations

2025 | **Stable Tungsten Isotope Dynamics at Variable Redox Conditions in the Baltic Sea** Goldschmidt Conference, Prague, Czech Republic.

Data

Physical oceanography (CTD):

<https://doi.org/10.5281/zenodo.17141378>

Trace metals (Mn and W) water column:

<https://doi.org/10.5281/zenodo.17141378>

Trace metals (Mn and W) porewater:

<https://doi.org/10.5281/zenodo.17141378>

Mercury in sediments:

<https://doi.org/10.5281/zenodo.17141378>

Cruise Report

EMB324: https://doi.org/10.48433/cr_emb324

HE573, HE584, HE596, HE607 and HE613

Risk assessment of war wrecks – a comprehensive approach investigating wrecks containing munitions in the North Sea

Authors

**Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research |
Bremerhaven, Germany**
M. Brenner

Abstract

Shipwrecks and dumped munition continue to be a major hazard, both in the North Sea but also on a global scale. For the whole North Sea, about 1000 wrecks with military background are estimated of which approx. 120 military ship- and aircraft wrecks (Grassel et al., 2021) from WW I and II ended up within the German Exclusive Economic Zones (EEZ) according to data from the German Maritime Agency, Hamburg. Research within the EU Interreg project North Sea Wrecks (NSW), is generating new insights into the status of wrecks, the potential leakage of pollutants from remaining munitions loads and the effects of contamination on exposed marine organisms in the North Sea environment. In close cooperation with project and associated partners from Belgium, Netherlands, Denmark and Norway 15 war wrecks ranging from destroyers, over submarines to converted fishing vessels from both WWI and II were investigated in detail.

Only identified war wrecks, not being silted up and accessibility for divers were selected for further investigations (Figure 1). In addition, historical documents were generated from archives to describe ship's history and sinking scenario. This information was also used for the calculation of munition remains onboard. Priority was given to wrecks still containing munitions onboard by the time of

sinking. In addition, samples of water, sediment and organisms were taken close to the wreck and subsequently analysed for traces of explosives. For munition the most important substances is 2,4,6-trinitrotoluene (TNT), used commonly as an explosive for military applications. It is known for its toxicity and to be mutagenic and carcinogenic. In the marine environment, corrosion ultimately results in the leakage of TNT from underwater munitions, affecting the surrounding sediments and biota (e. g. Koske et al. 2020, Maser et al. 2023 & Kammann et al. 2024), and potentially accumulating in the food web.

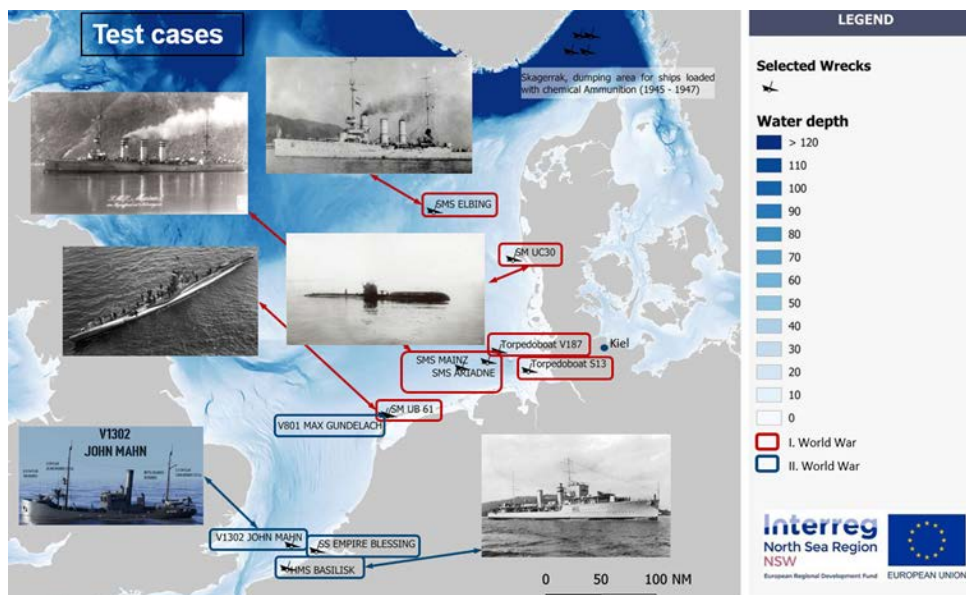


Figure 1: Examples of the investigated wrecks during the project North Sea Wrecks (NSW). Different types of wrecks from both World Wars were selected in the waters of partner countries (Graphic NSW 2021).

Combining the results of these different fields of research allows for a better understanding of the environmental risks deriving from these wrecks. Available data about the wrecks were assessed using a wreck risk model. Finally, wrecks were ranked according to their potential environmental risk.

Within the frame of the NSW project five 5-day RV Heincke cruises HE573, HE584, HE596, HE607 and HE613 were conducted to investigate the wrecks of SMS Mainz, SMS Ariadne, SMS Hela, Sperrbrecher Friesland, Vigo, S13 and V187 in the German Bight as well as the submarine UC30 laying today in Danish waters close to Esbjerg.

Aims of the cruises were to map the wrecks according to their bathymetry and magnetometry, to trace dissolved explosives in sediment and surrounding waters and to investigate microbial and infauna communities as well as bottom dwelling

fish species and blue mussels regarding the impact of dissolved explosives on community structure and health of the investigated organisms.

References

Grassel P, Otte F & Bergmann S, “Militärische Altlasten im Meer: ein gefährliches Erbe. Das Projekt North Sea Wrecks,” in Nachrichten des Marschenrates 2021, vol. 58, (Wilhelmshaven, Germany: Marschenrat zur Förderung der Forschung im Küstengebiet der Nordsee e. V), 13–17.

Koske D, Straumer K, Goldenstein, NI, Hanel R, Lang T & Kammann U, First evidence of explosives and their degradation products in dab (*Limanda limanda* L.) from a munition dumpsite in the Baltic Sea, Marine Pollution Bulletin 2020, 155, 111131, <https://doi.org/10.1016/j.marpolbul.2020.111131>.

Strehse JS, Bünning TH, Koschorreck J, Anita Künitzer A & Maser E, Long-Term Trends for Blue Mussels from the German Environmental Specimen Bank Show First Evidence of Munition Contaminants Uptake, Toxics 2023, 11, 347, <https://doi.org/10.1016/j.marpolbul.2020.111131>.

Kammann U, Töpker V, Schmidt N, Rödiger M, Aust MO, Gabel M & Scharsack JP, Explosives leaking from dumped munition contaminate fish from German coastal waters: a reason for chronic effects?, Environmental Sciences Europe 2024, 36, 116, <https://doi.org/10.1186/s12302-024-00942-5>.

Scientific Output

List of Publications

Grassel P, (submitted), Der Kleine Kreuzer SMS HELA, Gefahren und Gefährdung eines Wracks der Kaiserlichen Marine aus dem Ersten Weltkrieg, Deutsches Schifffahrtsarchiv.

Grassel P, (submitted), The German light cruisers SMS MAINZ and SMS ARIADNE, Investigating two First World War naval wrecks sunk in the Battle of Heligoland Bight 1914, International Journal of Nautical Archaeology.

Bergmann S, Brenner M, Strehse JS, Bünning TH, Maser E, Grassel P, Heuskin D, Brandt D, Berger M, van der Wulp S, Skellhorn M, Hill P, Van Haelst S, De Rijcke M & Wichert U, Risk assessment of war wrecks – a comprehensive approach investigating four wrecks containing munitions in the German Bight/North Sea, *Propellants, Explosives & Pyrotechnic* 2024, 49, e202300322, <https://doi.org/10.1002/prep.202300322>.

Grassel P, Versenkt im Ersten Weltkrieg – Erforschung, Gefahren und Gefährdungen des Wracks des Kleinen Kreuzers SMS ARIADNE, *Siedlungs- und Küstenforschung im südlichen Nordseegebiet* 2024, 47, 339–363.

Grassel P, Der Kleine Kreuzer SMS MAINZ – Erforschung, Gefahren und Gefährdung eines Kriegswracks aus dem Ersten Weltkrieg, *Siedlungs- und Küstenforschung im südlichen Nordseegebiet* 2023, 46, 237–270.

Bergmann S & Grassel P, Mikroplastik und TNT. Unterschiedliche Regime der Problematisierung von Meeresmüll, *Werkstatt Geschichte* 2022, 85, 55–75.

Grassel P, Kellermann J, Riml C & Bergmann S, Toxic Legacies of War. Die Wanderausstellung zum Forschungsprojekt „North Sea Wrecks“, *Deutsche Schifffahrt, Informationen des Fördervereins Deutsches Schifffahrtsmuseum e. V.* 2022, 1, 27–30.

Grassel P, Ammunition on Wrecks. Researching Military Wrecks in the German Bight, *Skyllis, Zeitschrift für maritime und limnische Archäologie und Kulturgeschichte* 2022, 89–100.

Grassel P, Otte F & Bergmann S, “Militärische Altlasten im Meer: ein gefährliches Erbe. Das Projekt North Sea Wrecks,” in *Nachrichten des Marschenrates* 2021, vol. 58, (Wilhelmshaven, Germany: Marschenrat zur Förderung der Forschung im Küstengebiet der Nordsee e. V), 13–17.

List of conference presentations

Oral Presentations

2025 | **No time to waste: Tackling submerged munitions in European seas**, RV Meteor Event – Thematic Island: Environmental Risks of Munition in the Sea at United Nation Ocean Conference, Nice, France

2025 | **Lost Ships, Lasting Impacts: Managing Shipwreck Pollution Through Archival and Environmental Science**, 8th International Congress for Underwater Archaeology IKUWA, Oostend, Belgium

2025 | **Tackling the topic munition at sea – 15 years of research in North and Baltic Sea**, Environmental Impacts of War at Arctic Frontiers Conference 2025, Tromsø, Norway

2025 | **Heritage of war – a multi-biomarker approach to investigate the effects of sunken warship wrecks on common dab (*Limanda limanda*) in the North Sea**, Environmental Impacts of War at Arctic Frontiers Conference 2025, Tromsø, Norway

2024 | **Effekte von Explosivstoffen auf marine Organismen – Erste Ergebnisse von Munitions-Hotspots der Nordsee**, Meeresumweltsymposium 2024, Hamburg, Germany

2024 | **War wrecks and their environmental impact**, NATO Science for Peace and Security Program – NATO Advanced Study Institute, Workshop Monitoring and Assessment of hazardous underwater objects in the global ocean: an integrated approach, Birgu, Malta

2024 | **Heritage of war – a multi-biomarker approach to investigate the effects of sunken war wrecks on common dab (*Limanda limanda*) in the North Sea**, Legacy of War: Environmental Contamination, Ecotoxicity and Human Health Concerns of Explosives and Chemical Warfare Agents at 34 Annual Meeting of Society of Environmental Toxicology and Chemistry (SETAC), Sevilla, Spain

Poster Presentations

2025 | **Depuration kinetics of TNT and its metabolites in lab exposed blue mussels (*Mytilus edulis*, L.)**, Environmental Impacts of War at Arctic Frontiers Conference 2025, Tromsø, Norway

2024 | **Heritage of war – a multi-biomarker approach to investigate the effects of sunken war wrecks on common dab (*Limanda limanda*) in the North Sea**, 34 Annual Meeting of Society of Environmental Toxicology and Chemistry (SETAC), Sevilla, Spain

2023 | **Biological effects of munition left on war wrecks on the health of caged blue mussels (*Mytilus edulis*, L.) in the southern North Sea**, General Assembly of the European Geosciences Union 2023 (EGU), Vienna, Austria

2023 | **Are war wrecks and their munition cargo posing health risks to fish? – A multi-biomarker assessment of dabs (*Limanda limanda*) living at wreck sites in the southern North Sea**, General Assembly of the European Geosciences Union 2023 (EGU), Vienna, Austria

2022 | **Wracks im Visier: Das Projekt North Sea Wrecks untersucht und bewertet Weltkriegswracks und ihre Munitionsaltlasten hinsichtlich ihrer Umweltgefahren**, Küstenforschung Nordsee-Ostsee, 3. Küstensymposium „Küste im Wandel – Coast in Transition 2022“, Hamburg, Germany

2022 | **North Sea Wrecks – An interdisciplinary approach towards understanding the risks posed by wrecks containing munitions in the North Sea**, European Workshop on Maritime Systems Resilience and Security (MARESEC 2022), Bremerhaven, Germany

Data

Tippenhauer, Sandra; Hoppmann, Mario; Brenner, Matthias (2023): Physical oceanography during RV HEINCKE cruise HE613 [dataset]. PANGAEA: <https://doi.org/10.1594/PANGAEA.963432>

Tippenhauer, Sandra; Hoppmann, Mario; Brenner, Matthias (2023): Physical oceanography during RV HEINCKE cruise HE607 [dataset]. PANGAEA: <https://doi.org/10.1594/PANGAEA.961717>

Tippenhauer, Sandra; Hoppmann, Mario; Brenner, Matthias (2023): Physical oceanography during RV HEINCKE cruise HE596 [dataset]. PANGAEA: <https://doi.org/10.1594/PANGAEA.950208>

Hoppmann, Mario; Tippenhauer, Sandra; Brenner, Matthias (2022): Continuous thermosalinograph oceanography along RV HEINCKE cruise track HE584 [dataset]. PANGAEA: <https://doi.org/10.1594/PANGAEA.944738>

Brenner, Matthias; Rohardt, Gerd (2021): Physical oceanography during HEINCKE cruise HE573 [dataset]. PANGAEA: <https://doi.org/10.1594/PANGAEA.931648>

Cruise Reports

HE573: https://doi.org/10.48433/cr_he573

HE584: https://doi.org/10.48433/cr_he584

HE596: https://doi.org/10.48433/cr_he596

HE607: https://doi.org/10.48433/cr_he607

HE613: https://doi.org/10.48433/cr_he613

HE590 and HE629

RoboLeaks: HE590 and HE629 expeditions

Authors

MARUM, University of Bremen | Bremen, Germany

R. Bachmayer, A. Kopf

And Shipboard Science Parties HE590 and HE629

The RoboLeaks cruise, initially granted for R/V Meteor/Merian, were carried out as two short legs on R/V Heincke, namely expedition HE590 and HE629, aimed to conduct intensive testing of newly developed seagoing equipment at gas seep sites in the North Sea and Baltic Sea. Two vehicles, the IMGAM AUV (developed between MARUM and ATLAS Elektronik) and a customized BlueRobotics miniature ROV based on a seafloor lander, were to be tested. Also, a new camera module for a seagoing glider was awaiting ocean testing. Finally, a new SEPRO heave-compensated winch, acquired to serve the MARUM H-ROV Ray6000, has also never been tested and requires sufficient water depth ($>50\text{m}$) and heavy weather/substantial heave for the testing.

The RoboLeaks-1 cruise HE590 took place from 10.–16.02.2022, in both Eckjernförde Bight and the vicinity of Bornholm, Baltic Sea. The expedition started and ended in Bremerhaven. Work at sea included intensive testing of newly developed seagoing equipment at gas seep sites in the Baltic Sea. The IMGAM AUV and a customized BlueRobotics miniature ROV, a camera module for a glider, and a new heave-compensated winch were tested successfully.

The IMGAM AUV missions included safe launch and recovery using a custom-built rollable base, trimming, basic surveying at variable speeds and water depths, were carried out in Eckjernförde Bight. During the nights between the AUV testing days, multibeam mapping and SIS Innomar sub-bottom profiling aimed at the identification of pockmarks and other seepage localities.

The heave-compensated winch, acquired to serve the MARUM H-ROV Ray6000, was tested in deeper waters close to the island of Bornholm, where a multi-

sensor platform (MSP) with a bottom weight was lowered together with the glider module, the BlueROV and IMUs (Inertia Monitoring Systems) to assess winch performance.

The expedition aboard the RV Heincke (HE629) focused on further evaluating the technical and operational capabilities of the new IMGAM AUV. The evaluation and test scenarios aimed to explore the AUV's potential and limitations, and to identify any shortcomings in its operation for future scientific missions. Although the AUV is designed for seep detection and sampling at depths of up to 2,000 metres, it had only been tested at depths of up to 50 metres prior to this expedition.

Future tasks will involve sonar-based seafloor and water column mapping, high-precision close-proximity opto-acoustic seafloor mapping, autonomous gas flare detection (seep mapping), and adaptive sampling. During this cruise, the vehicle was taken to increasingly greater depths and crucial independent surface and seafloor navigation performance tests were conducted. The R2Sonic 2026 multi-beam sonar system was tested and calibrated by collecting seafloor bathymetry and water column data during short dives. The work area was predominantly around the greater Stavanger Fjord due to favourable test conditions with respect to water depth while adverse weather conditions prevailed outside the fjord. The final work area was set in the Skagerrak region, where IMGAM's seep detection capabilities were to be tested at documented seafloor seep sites. Although the vehicle's performance characteristics, including the multi-beam sonar's interaction with the navigation system, were successfully established, no seeps could be detected using the ship-mounted multibeam or the AUV's sonar system.

The cruise departed from Stavanger on the morning of 3rd October 2023, heading for the first work area, and concluded in Bremerhaven in the evening of 9th October 2023. A total of 24 AUV dives were conducted during the eight days at sea, representing an extremely efficient testing regime thanks to the excellent support by the crew and vessel, as well as the fjord region providing an excellent testing ground.

Scientific Output

List of conference presentations

2024 | **SPiraling Intelligent Robotic Underwater monitoring pLAtform (SPIRULA)-towards repeated, high density and low-cost seafloor monitoring**, IEEE/OES Autonomous Underwater Vehicles Symposium (AUV), San Francisco, USA.

Cruise Reports

HE590: https://dx.doi.org/10.48433/cr_he590

HE629: n/a

HE595

The Helgoland Mud Area: Understanding Carbon Sinks in Dynamic Shelf Seas

Authors

**Alfred-Wegener-Institute, Helmholtz Centre for Polar- und Marine Research |
Bremerhaven/Sylt, Germany**

M. Holtappels, U. Hanz, S. Henkel, S. Kasten, B. Liu, D. Müller, L. Sanders, B. Wei

Helmholtz Centre Hereon | Geesthacht, Germany

J. Chen, L. Portz, W. Zhang

**Center for Marine Environmental Sciences – MARUM, University of Bremen, |
Bremen, Germany**

M. Holtappels, S. Kasten, B. Wei

The Helgoland Mud Area

Continental shelf seas, though small in areal extent, are disproportionately important to global biogeochemical cycles, accounting for roughly half of the marine organic carbon (OC) burial and thus representing a significant long-term sink of particulate organic carbon (POC) (Berner and Berner, 2012). However, shelf sediments are heterogeneously distributed with more than 50% consisting of sands (Emery 1968) where strong tides and currents prevent POC accumulation. Within these energetic environments, some localized mud depocenters can be found due to specific hydrodynamic conditions that act as natural sediment traps. In the German Bight, the Helgoland Mud Area (HMA) is the most prominent of these depocenters. It represents a shallow (15–40 m depth) accumulation zone of fine-grained, organic-rich sediment within an otherwise sand-dominated shelf setting (Hebbeln et al. 2003). Despite its limited spatial extent the HMA is a keystone site for understanding the coupling of physical transport, sedimentation, and carbon cycling in high-energy coastal systems.

To unravel the processes that sustain this depocenter and its role in carbon sequestration, a research cruise with FS HEINCKE (HE595), was conducted as part

of the BMBF Project APOC “*Anthropogenic impacts on the cycling of particulate organic carbon in the North Sea*”, combining hydrodynamic observations, sedimentological and geochemical analyses, benthic process studies, and anthropogenic impact assessments. The integrated insights from these efforts provide a holistic picture of how the HMA functions as a carbon sink and how it depends on regional hydrodynamics and coastal matter fluxes. It further provides a natural testbed to investigate the effect of regular sediment resuspension on the carbon burial efficiency, a knowledge gap that urgently needs to be addressed, as shelf sediments worldwide are being disturbed by extensive bottom trawling (Zhang et al. 2024).

RV Heincke expedition HE595

During the HE595 expedition from March 17 to April 3, 2022, the various sedimentary habitats of the HMA were sampled for geochemical analysis (Figure 1) to quantify rates of OC accumulation, degradation and burial in the sediments. Van-Veen grabs (75x), multi-corers (MUC 31x), and gravity cores (SL 15x) were used for extensive sediment sampling during the cruise. Further, a benthic observatory was deployed to measure hydrodynamics and particulate suspended matter (SPM) dynamics in the water column at seven stations along an east-west transect across the HMA. Over a period of two tidal cycles (24 h), hydroacoustic measurements were used to determine flow velocity, turbulent transport, and SPM concentration, the latter being calibrated with an automated in-situ SPM filtration device. At the same time, Yo-Yo-CTD deployments (altogether 256x) were carried out to observe water column state and SPM concentrations over the tidal cycle. O₂ incubations of water samples were conducted to determine the remineralization rates of POC as a function of tidal phase and water depth. The benthic observatory was also used to investigate an artificial benthic disturbance caused by the bottom trawl of the research vessel UTHÖRN.

The analysis of sediment samples on shore included radionuclide measurements (²¹⁰Pb and ¹³⁷Cs), solid-phase analyses (grain size spectra, porosity), analyses of particulate (organic) carbon (TC, TOC, $\delta^{13}\text{C}$ -POC, fatty acid markers), as well as pore water analyses of dissolved inorganic carbon (DIC and $\delta^{13}\text{C}$ -DIC), nutrients (nitrate, ammonium, phosphate, silicate) and other reactive compounds (Mn(II), Fe(II), sulfate). The SPM samples were analyzed for carbon content and isotopy. The data was used for full diagenetic modelling and as comparison for numerical reactive transport models simulating regional SPM and POC transport and accumulation.

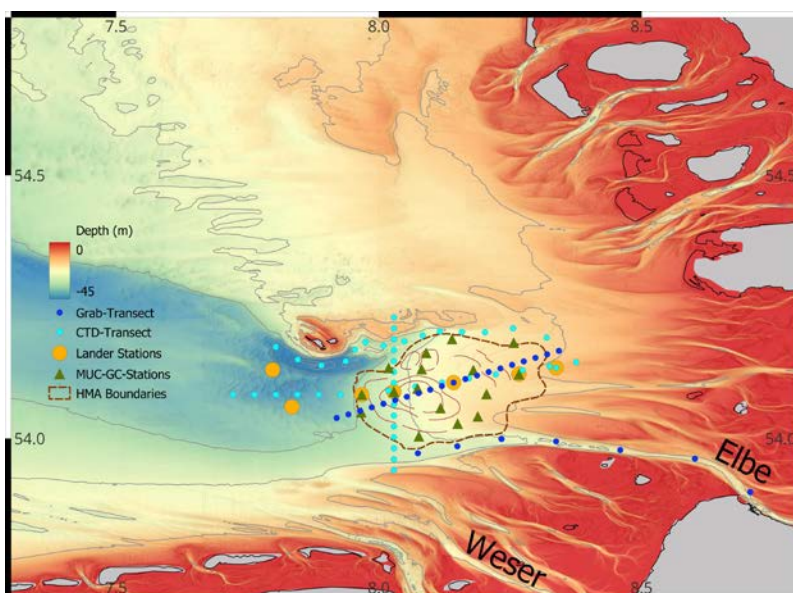


Figure 1: Stations in the Helgoland Mud Area (HMA) sampled for sediments and water column, as well as “Lander Stations” of the benthic observatory. Bathymetry from EasyGSH. Isolines show 15, 25 and 35 meter depth contour.

Characteristics of the HMA carbon sink

Sediment Accumulation and Carbon Burial Efficiency

Sedimentation rates across the HMA range between 0.5 and 4.5 mm yr⁻¹, with organic carbon contents from 0.2–2.0 wt% (Müller et al. 2025). The highest values occur in the southern HMA, influenced by Elbe and Weser estuarine inputs. Isotopic analyses show that roughly 75% of POC is terrestrial, while 25% is marine in origin (Wei et al. 2025). Terrestrial material exhibits higher burial efficiency, while the analysis of $\delta^{13}\text{C}$ -DIC and bacterial lipids indicate that marine OC is preferentially remineralised. Organic carbon in sediments is mainly degraded through aerobic respiration and sulfate reduction, with total remineralization rates of 1.2–6.3 mmol C m⁻² d⁻¹. (Müller et al. in review). Calculated burial rates vary from 4–57 g C m⁻² yr⁻¹, averaging 22.5 g C m⁻² yr⁻¹ across the HMA, equivalent to about 11,250 tons of organic carbon stored annually (Müller et al. 2025). Despite strong tidal currents, these values match those from deep depositional basins like the Skagerrak and Norwegian Trench. The results from sediment analysis indicate that sedimentation rate is the key factor controlling organic carbon preservation, as higher rates reduce oxygen exposure time. The highest burial efficiencies (>65%) occur in areas with high sedimentation and terrestrial input, while the lowest (~30%) appear in shallow, low-sedimentation zones.

Sediment Dynamics and Resuspension

Tidal currents in the German Bight cause intense cyclic resuspension of sediment. Measurements from the benthic observatory show that about 500 g of sediment per m² is resuspended and redeposited during each tidal cycle (Hanz et al, in prep for ES&T). Despite this high resuspension, net accumulation still occurs due to restricted lateral transport under stratified hydrographic conditions. Stratification, driven by freshwater inflows and summer warming, inhibits vertical mixing and favors local deposition (Chen et al. 2025). However, resuspension leads to significant aerobic remineralization of suspended matter. Experiments indicate an average carbon remineralization rate of 0.65 g C m⁻² day⁻¹ (≈ 237 g C m⁻² yr⁻¹), nearly ten times the burial rate. When this is accounted for, the effective carbon burial efficiency of the HMA decreases from over 50% to less than 10%. Accordingly, it was found that locations with a strong sediment resuspension have a significantly decreased OC reactivity as determined by full diagenetic modelling. In summary, while the HMA is a significant carbon sink, it also has a high carbon footprint.

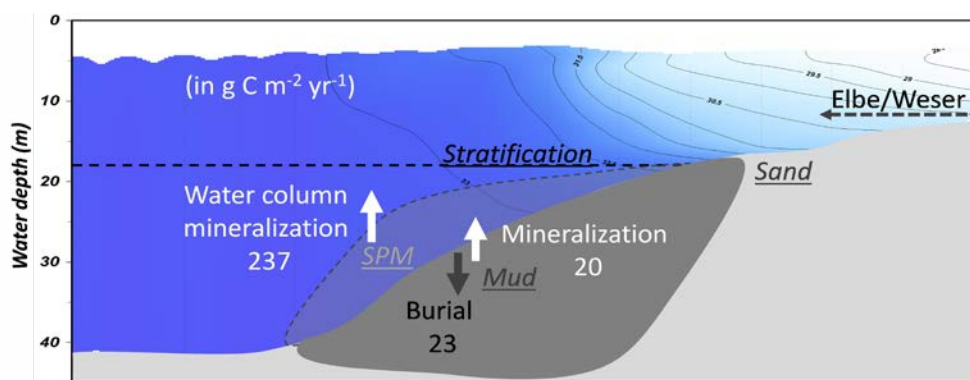


Figure 2: Organic carbon fluxes in the Helgoland Mud Area. Carbon burial and remineralization in the sediments were determined from sediment samples (Müller et al. 2025). The OC concentration and remineralization in the water column was determined from filtration and O₂ incubation experiments (Hanz et al, in prep). High SPM concentrations caused by tidal sediment resuspension result in 10-fold higher mineralization rates compared to sediments. The stratification of the water column (salinity shown in color) prevents the transport of suspended material toward the coast (Chen et al. 2025).

Anthropogenic Disturbance and Trawling Impact

To assess the impact of trawling activities, a disturbance experiment was performed using a beam trawl deployed upstream of the observatory. The trawl generated a plume of suspended sediment, 3.5 m high and up to 90 m wide, with increased SPM concentrations of up to 125 mg L⁻¹ - two to three times the natural background (Hanz et al. in prep). Calculations suggest that under these conditions, each kilometer of trawling releases approximately 7 kg of CO₂.

Comparison of stations with similar sediment types but differing trawling intensity indicates that frequent bottom trawling reduces carbon burial efficiency by about 30%. These findings align with recent modeling studies showing that trawling disturbs fine sediments, promotes organic matter oxidation, and diminishes long-term carbon storage potential (Zhang et al. 2025).

References

Berner EK & Berner RA, *Global Environment: Water, Air and Geochemical Cycles*, 2nd edition ed. 2012, Princeton University Press, Princeton, New Jersey.

Chen J, Zhang W, Porz L, Arlinghaus P, Hanz U, Holtappels M & Schrum C, Physical Mechanisms of Sediment Trapping and Deposition on Spatially Confined Mud Depocenters in High-Energy Shelf Seas, *Journal of Geophysical Research: Oceans* 2025, 130(7), doi:10.1029/2025JC022622.

Emery KO, Relict sediments on continental shelves of world, *American Association of Petroleum Geologists Bulletin* 1968, 52(3), 445–464.

Hebbeln D, Scheurle C & Lamy F, Depositional history of the Helgoland Mud Area, German Bight, North Sea, *Geo-Marine Letters* 2003, 23(2), 81–90.

Müller D, Liu B, Geibert W, Holtappels M, Sander L, Miramontes E, Taubner H, Henkel S, Hinrichs KU, Bethke D, Dohrmann I & Kasten S, Depositional controls and budget of organic carbon burial in fine-grained sediments of the North Sea – the Helgoland Mud Area as a natural laboratory, *Biogeosciences* 2025, 22(11), 2541–2567, doi:10.5194/bg-22-2541-2025.

Wei B, Müller D, Kusch S, Niu L, Hefter J, Sander L, Hanz U, Mollenhauer G, Jia G, Kasten S & Holtappels M, Twice the global average carbon burial efficiency in the Helgoland Mud Area of the North Sea: Insights into carbon sequestration in small-size depocenters on sand-dominated shelves, *Chemical Geology* 2025, 681, 122712.

Zhang W, Porz L, Yilmaz R, Wallmann K, Spiegel T, Neumann A, Holtappels M, Kasten S, Kuhlmann J, Ziebarth N, Taylor B, Ho-Hagemann HTM, Daewel U & Schrum C, Intense and persistent bottom trawling impairs long-term carbon storage in shelf sea sediments, *Nature Geoscience* 2024, doi:10.1038/s41561-024-01581-4.

Scientific Output

List of Publications

Chen J, Zhang W, Porz L, Arlinghaus P, Hanz U, Holtappels M & Schrum C, Physical Mechanisms of Sediment Trapping and Deposition on Spatially Confined Mud Depocenters in High-Energy Shelf Seas, *Journal of Geophysical Research: Oceans* 2025, 130(7), doi:10.1029/2025JC022622

Hanz U, Wei B, Sander L, Kopte R, Kasten S & Holtappels M, (in prep. for *Environmental Science & Technology*) The influence of hydrodynamics on the carbon burial efficiency above a carbon depositional area on a shallow continental shelf.

Liu B, Müller D, Henkel S, Geneste C & Kasten S, (in prep.) Carbon diagenesis and long-term burial as carbonate in the sediment of the Helgoland Mud Area, SE German North Sea.

Müller D, Liu B, Geibert W, Holtappels M, Sander L, Miramontes E, Taubner H, Henkel S, Hinrichs KU, Bethke D, Dohrmann I & Kasten S, Depositional controls and budget of organic carbon burial in fine-grained sediments of the North Sea – the Helgoland Mud Area as a natural laboratory, *Biogeosciences* 2025, 22(11), 2541-2567, doi:10.5194/bg-22-2541-2025.

Müller D, Liu B, Holtappels M, Geibert W, Henkel S & Kasten S, (in review at *Continental Shelf Research*) Rates and pathways of organic matter remineralisation in different sedimentary environments of the Helgoland Mud Area, North Sea.

Müller D, Wollenburg J, Grotheer H, Mollenhauer G, Geibert W, Liu B & Kasten S, (in prep. for *Limnology and Oceanography*) Spatio-temporal variability and controls on sediment and organic carbon accumulation over centennial timescales in the Helgoland Mud Area.

Wei B, Müller D, Kusch S, Niu L, Hefter J, Sander L, Hanz U, Mollenhauer G, Jia G, Kasten S & Holtappels M, Twice the global average carbon burial efficiency in the Helgoland Mud Area of the North Sea: Insights into carbon sequestration in small-size depocenters on sand-dominated shelves, *Chemical Geology* 2025, 681, 122712.

Wei B, Waska H, Grotheer H, Dittmar T & Holtappels M, (in prep.) DOM dynamics at sediment-water interface in the North Sea: Implication for global benthic DOM fluxes.

List of conference presentations

2023 | **Depositional processes, particulate organic carbon contents and origin across the Helgoland Mud Area, SE German Bight**, EGU General Assembly, Vienna, Austria

2023 | **Carbon remineralization and long-term burial as carbonate in muddy North Sea sediments**, American Geophysical Union Fall Meeting, San Francisco, USA

2023 | **Results from the project APOC – The role of marine sediments as carbon sink and the impact of bottom trawling on seafloor carbon sequestration**, International Workshop “Progress in Marine Conservation” of the Bundesamtes für Naturschutz (BfN), Stralsund, Germany

2023 | **Depositional processes and controlling factors for the preservation of particulate organic matter in the Helgoland Mud Area, SE German Bight**, ICMARE, Oldenburg, Germany

2023 | **Depositional conditions controlling organic carbon burial in fine-grained sediments of the North Sea – The Helgoland Mud Area as a test field**, GeoBerlin, Berlin, Germany

2023 | **Die Rolle von Sedimenten als natürliche Kohlenstoffsенke und die Auswirkungen von Grundschieppnetzфischerei auf die Kohlenstoffspeicherung im Meeresboden – das Projekt APOC**, Fachworkshop “Blue Carbon” des Bundesamtes für Naturschutz (BfN), Rostock, Germany

2023 | **Das BMBF Projekt APOC – Anthropogene Einflüsse auf den Kreislauf partikulären organischen Kohlenstoffs in der Nordsee**, Scoping Workshop der Deutschen Volkswagenstiftung, Hannover, Germany

2024 | **Particulate organic carbon dynamics of a depositional area in a high-energy shelf environment**, EGU General Assembly, Vienna, Austria

2024 | **Assessing the sedimentary carbon sink for climate change mitigation – the need for transdisciplinary cooperation**, EGU General Assembly, Vienna, Austria

Data

Master track and station list:

<https://doi.org/10.1594/PANGAEA.945422>

Continuous thermosalinograph oceanography along RV HEINCKE cruise track HE595:

<https://doi.org/10.1594/PANGAEA.963411>

Physical oceanography during RV HEINCKE cruise HE595:

<https://doi.org/10.1594/PANGAEA.948067>

Pore-water pH, H₂S, Cl⁻, SO₄²⁻, SiO₂, NO₂⁻, PO₄³⁻, NH₄⁺, NO₃⁻, major and trace element data from MUC cores taken during RV HEINCKE cruises HE575 and HE595 in the Helgoland Mud Area, German Bight:

<https://doi.org/10.1594/PANGAEA.983802>

Geochemical properties in surface sediments of the Helgoland Mud Area and surrounding sandy areas taken during HEINCKE cruise HE595 in the North Sea:

<https://doi.org/10.1594/PANGAEA.971520>

Pore-water DIC and $\delta^{13}\text{C}$ -DIC data, as well as solid-phase porosity and TOC data from a MUC core from RV HEINCKE cruise HE595 at Tonne E3 in the Helgoland Mud Area, SE German Bight:

<https://doi.org/10.1594/PANGAEA.983806>

Pore-water dissolved inorganic carbon (DIC) and its stable carbon isotopic composition ($\delta^{13}\text{C}$) for sediment cores taken during RV Heincke cruise HE575 and HE595 in the Helgoland Mud Area, German Bight:

<https://doi.org/10.1594/PANGAEA.969033>

Raw data of physical oceanography during RV HEINCKE cruise HE595:

<https://doi.pangaea.de/10.1594/PANGAEA.966956>

Solid-phase porosity, grain sizes, TOC, 210Pbxs and 137Cs data for sediment cores taken during RV Heincke cruise HE575 and HE595 in the Helgoland Mud Area, SE German Bight:

<https://doi.org/10.1594/PANGAEA.968969>

Oxygen micro profiles of multi-corer sediment cores taken during RV Heincke cruise HE595 in the Helgoland Mud Area, SE German Bight:
<https://doi.org/10.1594/PANGAEA.970325>

Concentrations and loadings of alkanes in surface sediments of Helgoland Mud Area in the North Sea:
<https://doi.org/10.1594/PANGAEA.971522>

Concentrations and loadings of fatty acids in surface sediments of Helgoland Mud Area in the North Sea:
<https://doi.org/10.1594/PANGAEA.971523>

Organic carbon (OC) content, nitrogen content, C/N ratio, carbonate content, $\delta^{13}\text{C}$ of OC, mean grain size, surface area, calculated fraction, content and loading of terrestrial and marine OC in surface sediments of Helgoland Mud Area in the North Sea:
<https://doi.org/10.1594/PANGAEA.971521>

Cruise Report

Not available

HE598, HE609, HE614 and HE626

Essential Climate Variables in the Ocean's Skin and Near-Surface Layer

Authors

Institute of Chemistry and Biology of the Marine Environment, Centre of Marine Sensors (ZfMarS), University of Oldenburg | Wilhelmshaven, Germany

O. Wurl, S. M. Ayim, M. Ribas Ribas, L. Jaeger, J. Meyerjürgens, T. Badewien, C. Lehnert, L. Gassen-Bertzach

The North Sea is particularly susceptible to the impacts of climate change, which have significant societal implications for coastal populations. To aid policymakers in making strategic decisions, it is essential to conduct long-term, region-wide monitoring of essential climate variables (ECVs) to evaluate climate change trends. Remote-based satellite observations offer a cost-effective solution, providing comprehensive spatial coverage within days – a feat unattainable through traditional hydrographic surveys using ships and monitoring buoys. However, calibrating and validating remote-sensed satellite data pose challenges due to discrepancies in measurement depths between satellite signals and in-situ data, as well as interference from land-based contamination. During four cruises on the RV Heincke (SCANS cruises), we collected data from the “true” sea surface to avoid depth mismatches and conducted transects from the coast to the open North Sea to assess land contamination. Our goal has been to obtain high-resolution in-situ data – both spatially and temporally – to provide representative averaged in-situ data for individual grids within the satellite’s footprint and to assess and explain the variability of ECVs within these grids. Ultimately, we have aligned our sea surface data with satellite observations of the two key ECVs: sea-surface temperature (SST) and salinity (SSS). Based on the acquired datasets, new digital technology utilizing explainable artificial intelligence (XAI) algorithms are developed with a framework described by Miedtank et al. (2024).

With the SCANS cruises, the design, development, and operation of the autonomous research vehicle (ASV) HALOBATES have been completed (Wurl et al.,

2024). HALOBATES' automated operation enables high-resolution mapping of the oceanic skin layer, targeting the upper 1-mm layer and the near-surface layer (NSL) at a depth of 1.2 meters. A rotating glass disk assembly is used to sample the skin layer. For this purpose, HALOBATES is equipped with a set of eight conductivity – temperature – depth (CTD) sensors, which are integrated into a flow-through system to measure both the skin and NSL temperatures and salinity. Autonomous operation has been evaluated under various scenarios typical of the coastal and open North Sea. Typical anomalies of ECVs within the skin and NSL have been observed and found to be influenced by both atmospheric and oceanic processes. Data analysis schemes were developed to demonstrate HALOBATES' capability to resolve thermohaline structures over multiple spatial and temporal scales, such as small-scale freshwater lenses, slicks, and sub-mesoscale thermohaline changes across oceanic fronts. Additionally, the integration of an acoustic Doppler current profiler has facilitated the interpretation of thermohaline structures by providing information on near-surface currents. Overall, HALOBATES is a cutting-edge technology for understanding climate-related processes between the ocean and atmosphere, and is applied in the project NorthSat-X to provide high-resolution sea surface data for validating satellite products of ECVs.

The lack of systematic comparison and potential discrepancy between in-situ and satellite observations highlights a significant challenge in ocean monitoring of ECVs (Boutin et al., 2016). Even so, biases are expected to be lower for skin temperature compared to skin salinity, due to the high resolution, multiple, and more advanced satellite observations of SST. A first evaluation of skin temperature was conducted to develop a scheme of data quality and analysis (Ayim et al., under review). During the SCANS cruises, HALOBATES was deployed to collect in-situ data for comparison with buoy and satellite data (Figure 1).

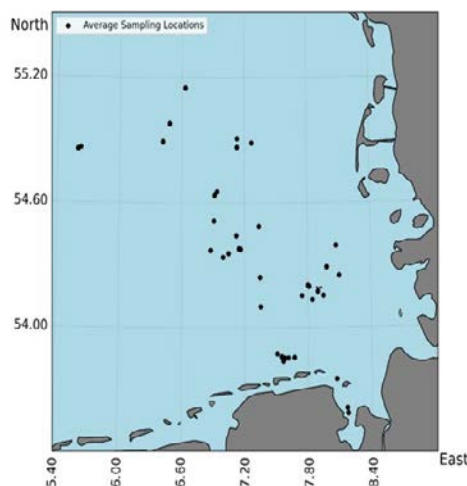


Figure 1: Study area within the North Sea with black dots indicating the average sampling position of HALOBATES during the NorthSat-X project.

Analysis revealed differences between the skin and NSL temperature. The skin layer exhibited greater variability in mean bias (-0.44 ± 0.60 °C) compared to the NSL (-0.40 ± 0.52 °C), indicating more pronounced temperature fluctuations at the skin layer, as expected due to evaporative cooling and diurnal warming. Furthermore, the root-mean-squared error was found to be 0.09 °C higher in the skin layer (0.75 °C) than in the NSL (0.66 °C). These findings suggest that remote-sensing observations may accurately represent the NSL, as the time resolution of satellite observation is much coarser than our in-situ observation, that is, day versus minutes. Higher variability and unique thermohaline features in the skin layer at fine scales (<1000 m) underscore the importance of considering the vertical temperature structure when interpreting satellite-derived SST data and highlight the need for further research to improve our understanding of the complex thermal dynamics at the sea surface (Figure 2).

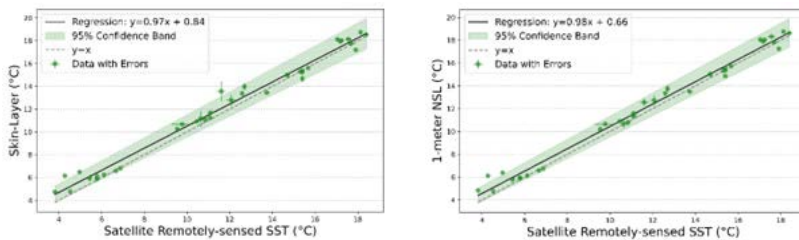


Figure 2: Deming regression plot showing the relationship between the different in-situ data and the remotely sensed SST: skin layer (left) and NSL (right). The black solid line represents the Deming regression fit, which accounts for the errors in both variables. The dashed grey line represents the reference line for a perfect 1:1 fit between the two variables. The green band is the 95% confidence interval of the slope. Both regressions closely follow the 1:1 line, with slopes near unity (0.97 and 0.98). The skin layer shows a slightly higher offset, while the 1 m layer exhibits marginally tighter agreement, indicating that satellite SST aligns more closely with NSL water temperatures than with the more atmosphere-sensitive skin layer.

Our initial assessment of the SSS shows greater errors compared to the temperature cross-comparison. The observed RMSE was 1.11 g kg^{-1} when compared with the NSL and slightly higher when compared with the skin layer (1.14 g kg^{-1}). The mean bias showed a similar trend, with lesser bias with the NSL (0.64 ± 0.93 g kg^{-1}) compared to the skin layer (0.68 ± 0.94 g kg^{-1}). The higher values of bias may be due to less advanced algorithms and coarser spatial and temporal resolutions in remotely sensed SSS retrievals, resulting in less accurate data compared to temperature retrievals. We found that precipitation leads to the formation of freshwater lenses in the North Sea, creating vertical temperature and salinity anomalies (Gassen et al., 2024). Our results indicated that remotely sensed SST and SSS exhibit a significant bias compared to in-situ observations, primarily due to differences in spatial and temporal scales. For example, remotely sensed SST underestimates in-situ observations by a few tenths of degrees Celsius, which are climatologically relevant.

References

Boutin J, Chao Y, Asher WE, Delcroix T, et al., Satellite and in situ salinity: Understanding near-surface stratification and subfootprint variability, *Bulletin of the American Meteorological Society* 2016, 97(8), 1391–1407.

Gassen L, Ayim SM, Badewien TH, Ribas-Ribas M & Wurl O, Wind speed effects on rainfall-induced salinity and temperature anomalies at the sea surface microlayer at mid-latitudes, *Elementa: Science of the Anthropocene* 2024, 12(1), 00004.

Wurl O, Gassen L, Badewien TH, Braun A, Emig S, Holthusen LA, Lehnert C, Meyerjürgens J & Ribas-Ribas M, HALOBATES: An Autonomous Surface Vehicle for High-Resolution Mapping of the Sea Surface Microlayer and Near-Surface Layer on Essential Climate Variables, *Journal of Atmospheric and Oceanic Technology* 2024, 41(12), 1197–1211, <https://doi.org/10.1175/JTECH-D-24-0021.1>.

Scientific Output

List of Publications

Gassen L, Ayim SM, Badewien TH, Ribas-Ribas M & Wurl O, Wind speed effects on rainfall-induced salinity and temperature anomalies at the sea surface microlayer at mid-latitudes, *Elementa: Science of the Anthropocene* 2024, 12(1), 00004, <https://doi.org/10.1525/elementa.2024.00004>.

Miedtank A, Schneider J, Manss C & Zielinski O, Marine digital twins for enhanced ocean understanding, *Remote Sensing Applications: Society and Environment* 2024, 36, 101268, <https://doi.org/10.1016/j.rsase.2024.101268>.

Wurl O, Gassen L, Badewien TH, Braun A, Emig S, Holthusen LA, Lehnert C, Meyerjürgens J & Ribas-Ribas M, HALOBATES: An Autonomous Surface Vehicle for High-Resolution Mapping of the Sea Surface Microlayer and Near-Surface Layer on Essential Climate Variables, *Journal of Atmospheric and Oceanic Technology* 2024, 41(12), 1197–1211, <https://doi.org/10.1175/JTECH-D-24-0021.1>.

List of conference presentations

2025 | **Detecting and Investigating Frontal Dynamics in the Skin Layer of the North Sea Using Autonomous Surface Vehicle Observations** EGU General Assembly, Vienna, Austria.

2024 | **Evaluating Satellite derived Sea-Surface Salinity in the North Sea with In-Situ Measurement from a Catamaran** Ocean Salinity Conference, Noordwijk, The Netherlands.

2024 | **HALOBATES – An autonomous surface vehicle to detect skin salinity at high spatial and temporal resolution** Ocean Salinity Conference, Noordwijk, The Netherlands.

2024 | **Skin Temperature and Salinity of the North Sea from an Autonomous Catamaran Compared to Satellite Observations** Ocean Sciences Meeting, New Orleans, USA.

2024 | **Measurements of sea surface salinity to detect freshwater fluxes at the ocean skin layer** Ocean Sciences Meeting, New Orleans, USA.

2022 | **The effect of rain on the sea surface** Ocean Salinity Conference, New York, USA.

Data

Physical oceanography:
<https://doi.pangaea.de/10.1594/PANGAEA.972989>

Physical oceanography:
<https://doi.org/10.1594/PANGAEA.966496>

Physical oceanography:
<https://doi.org/10.1594/PANGAEA.966495>

Physical oceanography:
<https://doi.org/10.1594/PANGAEA.974851>

Physical oceanography:
<https://doi.org/10.1594/PANGAEA.966465>

Physical oceanography:
<https://doi.org/10.1594/PANGAEA.968800>

Physical oceanography:
<https://doi.org/10.1594/PANGAEA.963423>

Physical oceanography:
<https://doi.org/10.1594/PANGAEA.968799>

Physical oceanography:
<https://doi.org/10.1594/PANGAEA.963414>

Cruise Reports

HE626: https://doi.org/10.48433/cr_he626
HE614: https://doi.org/10.48433/cr_he614
HE609: https://doi.org/10.48433/CR_HE609
HE598: https://doi.org/10.48433/cr_he598

HE601

Early stages of the benthic community at the pilot oyster reef in the german north sea

Authors

Alfred Wegener Institute Helholtz Centre for Polar and Marine Research | Bremerhaven, Germany

S.E.A. Pineda-Metz, H. Hoffmann, R.M. Düffert, M. Brand, B. Pogoda

The loss of habitats and biodiversity, accompanied by an increase in the number of threatened and rare marine species has resulted in an increase in protection measures. The constitution of the Natura 2000 network and associated protected areas is a clear example for European terrestrial and marine environments. According to the EU Marine Strategy Framework Directive (2008/56/EC), MPAs should contribute to a good environmental status of the European seas. Measures maintaining or restoring a favourable conservation status of protected species and habitats are mandatory according to the EU Habitats Directive (92/43/EEC). Within this legal context, two of the three marine protected areas (MAP) of the German Exclusive Economic Zone in the North Sea, namely the Borkum Reef Ground (BRG) and Sylt Outer Reef (SAR) MPAs, were defined as nature conservation areas (NSGBRgV, 2017). Additionally, the BRG MPA was identified as a suitable site and is now used for pilot studies for European flat oyster restoration (Merk et al. 2020; Pineda-Metz et al. 2023). The European flat oyster, *Ostrea edulis*, is a key reef-forming species in the North Sea and is of particular importance in terms of nature conservation (Pogoda et al. 2020).

Ostrea edulis reefs represent biodiversity hotspots, they provide food, shelter and settlement substrate for other benthic organisms (Pogoda et al. 2019). Due to their filtration capacity, European flat oyster reefs improve water quality by removing suspended material, decrease the risk of toxic algae blooms, and work as sediment trap, thus enhancing local benthic-pelagic coupling. Hence, *O. edulis* reefs provide valuable ecosystem services (Pogoda 2019; Pogoda et al. 2019). Nowadays, no intact European flat oyster reef remains due to intensive fishing pressure and other anthropogenic stressors. According to the Oslo-Paris

Convention (OSPAR), *O. edulis* is defined as an endangered key-species with a high ecological value and is listed as a high priority species for conservation and restoration within the Greater North Sea/Northeast-Atlantic region (OSPAR region II; OSPAR 2009).

Significant factors limiting the natural restoration of *Ostrea edulis* beds are still present: This includes, in particular, bottom trawl fishery in vast areas of the German North Sea. Another issue is the non-existent broodstock, which would be necessary to produce sufficient number of larvae for a self-sustaining population, as well as a lack of sufficient substrate for initial settlement (Kennedy & Roberts 1999). Previous work on growth and health in the course of offshore field studies in the German Bight showed already promising results (Merk et al. 2020). Current field experiments, done on board RV Heincke since 2017 within project RESTORE I & II documented outstanding growth, fitness and reproduction capacity of oysters. After the deployment of a pilot oyster reef within the BRG MPA in 2020 (Figure 1), new successional stages of benthic invertebrate communities could be defined for the pilot oyster reef, as well as a baseline benthic monitoring plan (Pineda-Metz et al. 2023). These results (Pogoda et al. 2020, Merk et al. 2020, Pineda-Metz et al. 2023) provide important information for further restoration attempts, as well as key insights in the development of a restored oyster reef since its deployment.

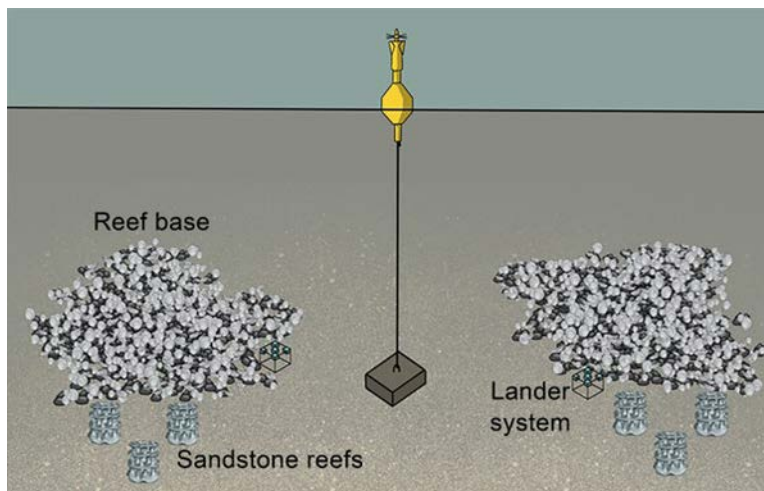


Figure 1: Technical scheme of the pilot oyster reef in Borkum Reef Ground, consisting of two reef areas with limestone reef base (boulders in dark grey), deployed oysters, as well as sandstone reefs and lander systems (including sensors for environmental parameters and broodstock oysters). The marker buoy (yellow) was installed and operated by the Federal Waterways and Shipping Administration (WSV). Modified after Pineda-Metz et al. (2023).

As above mentioned, monitoring of the restoration reefs has been conducted since 2021 using a combination of seabed images taken by divers (Pineda-Metz et al.

2023) and underwater videos made with the use of autonomous videos. The scientific activities of HE601 accounted for the former method, providing information of the development of the reef associated benthic community. Together with data collected since 2021, it can be used to define successional stages of reefs used for restoration of *O. edulis* reefs within Germany's MPAs. Results of the monitoring show data collected in 2021 and during HE601 to represent an early successional stage, with low abundance and species richness, where motile species such as the brown crab (*Cancer pagurus*) and colonizing anemone *Metridium senile* dominate. Results of later sampling campaigns show the community to have further developed (Figure 2), now *O. edulis* individuals, as well as new sessile species such as the octocoral *Alcyonidium digitatum* (dead man's hand), the sponge *Halichondria panicea*, and a higher species number and abundance can be observed on the reefs.

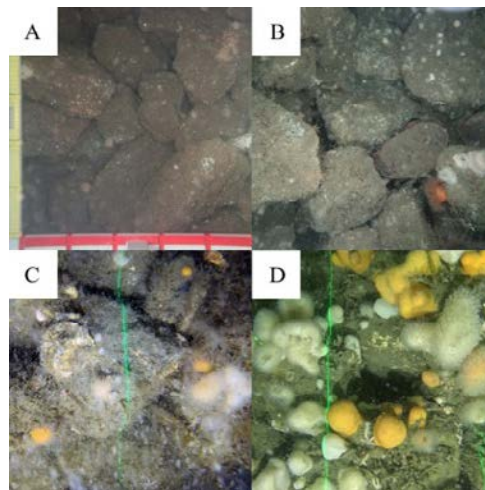


Figure 2: Examples of composition and development of the pilot oyster reefs in the Borkum Reef Ground Marine Protected Area. Pictures were taken in 2021 (A; Pineda-Metz et al. 2022), in 2022 during HE601 (B; Pineda-Metz et al. 2023b), in 2024 (C) and 2025 (D).

References

- Kennedy RJ & Roberts D, A Survey of the Current Status of the Flat Oyster *Ostrea edulis* in Strangford Lough, Northern Ireland, with a View to the Restoration of Its Oyster Beds, *Biological Environment* 1999, 99(2), 79–88.
- Merk V, Colsohl B & Pogoda B, Reintroducing native European oysters in the German North Sea: Growth, condition, and survival in offshore waters, *Aquatic Conservation: Marine and Freshwater Ecosystems* 2020, 30(11), 2180–2190. <https://doi.org/10.1002/aqc.3426>.

OSPAR, Background document for *Ostrea edulis* and *Ostrea edulis* beds, OSPAR Commission Biodiversity Series 2009, 428, 1–22.

Pineda-Metz SEA, Brand M, Merk V, Feuring A & Pogoda B, Seabed images taken at pilot oyster reefs in the Borkum Reef Ground marine protected area during September 2021 [dataset], PANGAEA 2022, <https://doi.org/10.1594/PANGAEA.941836>.

Pineda-Metz SEA, Colsohl B, Niewöhner M, Hausen T, Peter C & Pogoda B, Setting the stones to restore and monitor European flat oyster reefs in the German North Sea, *Aquatic Conservation: Marine and Freshwater Ecosystems* 2023a, 33(7), 661–677, <https://doi.org/10.1002/aqc.3945>.

Pineda-Metz SEA, Brand M & Pogoda B, Seabed images taken at pilot oyster reefs in the Borkum Riffgrund marine protected area during Heincke HE601 cruise (June 2022) [dataset], PANGAEA 2023b, <https://doi.org/10.1594/PANGAEA.963246>.

Pogoda B, Current Status of European Oyster Decline and Restoration in Germany, *Humanities* 2019, 8(1), 9. <https://doi.org/10.3390/h8010009>.

Pogoda B, Brown J, Hancock B, Preston J, Pouvreau S, Kamermans P, Sanderson W & von Nordheim H, The Native Oyster Restoration Alliance (NORA) and the Berlin Oyster Recommendation: bringing back a key ecosystem engineer by developing and supporting best practice in Europe, *Aquatic Living Resources* 2019, 32, 13, <https://doi.org/10.1051/alr/2019012>.

Pogoda B, Merk V, Colsohl B, Hausen T, Peter C, Pesch R, Kramer M, Jaklin S, Holler P, Bartholomä A, Michaelis R & Prinz K, Site selection for biogenic reef restoration in offshore environments: The Natura 2000 site Borkum Reefground as a case study for native oyster restoration, *Aquatic Conservation: Marine and Freshwater Ecosystems* 2020, 30(11), 2163–2179, <https://doi.org/10.1002/aqc.3405>.

Scientific Output

List of Publications

Sidorenko V, RubINETTE S, Akimova A, Pogoda B, AndrosOV A, Beng KC, Sell AF, Pineda-Metz SEA, Wegner KM, Brand SC, Shama LNS, Wollschlager J, Klemm K, Rahdarian A, Winter C, Badewien T, Kuzentsov I, Herrling G, Laakmann S & Wiltshire KH, Connectivity and larval drift across marine protected areas in the German bight, North Sea: Necessity of stepping stones, Journal of Sea Research 2025, 204, 102563, <https://doi.org/10.1016/j.seares.2025.102563>.

List of conference presentations

2023 | **The early stage of the associated benthic community at the pilot reef in the German North Sea** NORA 5, Middelburg, Netherlands.

2024 | **Exploring biodiversity refugia: Patterns of meroplankton biodiversity in the vicinity of restored oyster reefs** 7th Zooplankton production symposium, Hobart, Australia.

Data

Physical oceanography (CTD):
<https://doi.org/10.1594/PANGAEA.950213>

Seabed images of pilot oyster reefs:
<https://doi.org/10.1594/PANGAEA.963246>

Underwater videos:
<https://doi.org/10.1594/PANGAEA.974048>

Megabenthic abundance data:
<https://doi.org/10.1594/PANGAEA.974047>

Continuous thermosalinograph:
<https://doi.org/10.1594/PANGAEA.963416>

Master track:
<https://doi.org/10.1594/PANGAEA.947890>

Cruise Report

HE601: https://doi.org/10.48433/cr_he601

HE602, HE642 and HE659

MGF North Sea II: Effects of the exclusion of bottom-contact fishing on benthic habitats in the Natura 2000 sites 'Sylt Outer Reef' and 'Borkum Reef Ground'

Authors

Carl-von-Ossietzky University Oldenburg, Institute for Chemistry and Biology of the Marine Environment (ICBM) | Wilhelmshaven, Germany

S. Rohde

Helmholtz Centre Hereon | Geesthacht, Germany

A. Neumann, F. Minutolo

Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research | List, Germany

J. Hoffmann, L. Sander

Senckenberg am Meer | Wilhelmshaven, Germany

A. Bartholomä, G. Breyer

The research cruises HE602 (2022), HE642 (2024), and HE659 (2025) aboard RV HEINCKE were conducted within the framework of the German research missions on the exclusion and ecological effects of mobile bottom-contact fishing (MGF) in the North Sea, funded under the DAM Pilotmission and its continuation, the sustainMare mission "MGF-Nordsee-II" (www.mgf-nordsee.de). These consecutive expeditions were designed to provide an integrated, multi-annual effort to assess the ecological status and recovery potential of benthic habitats in Marine Protected Areas (MPAs) of the German Bight following the exclusion or reduction of trawling activities. Collectively, the cruises aimed to evaluate the physical, biogeochemical, and biological impacts of MGF along spatial gradients of fishing intensity in two core MPAs, the Sylter Outer Reef (SOR) and the Borkum Reef Ground (BRG), as well as in nearby reference sites.

HE602, conducted from June 23 to July 7, 2022, marked the initial phase of the DAM Pilotmission. The expedition established a methodological baseline for the integrated assessment of fishing impacts. At four sites per MPA along defined gradients of trawling intensity, the benthic fauna was surveyed by scientific diving, underwater video transects, and the deployment of Baited Remote Underwater Video systems (BRUVs). To assess benthic community structure and colonization potential, Autonomous Reef Monitoring Structures (ARMS) were deployed, while benthic landers recorded near-bottom hydrodynamics and nutrient dynamics. Incubation experiments on sediment cores were conducted to quantify nutrient fluxes and sediment–water exchange processes, allowing the estimation of bioturbation and bioirrigation activity in relation to varying degrees of physical disturbance. Hydroacoustic seafloor mapping, using a towed Side Scan Sonar (SSS), a hull-mounted Multibeam Echosounder (MBES), and a parametric Sub-Bottom Profiler (SES), provided the geomorphological context and guided all in-situ operations, including diving and lander deployments. The collected data delivered new insights into small-scale seafloor heterogeneity and enabled improved planning of follow-up missions.

HE642, carried out from May 30 to June 16, 2024, represented a continuation and methodological refinement of these studies under the sustainMare mission. The cruise successfully completed a series of benthic and biogeochemical investigations. In the Sylter Outer Reef, five sites were sampled along a fishery intensity gradient, whereas one site was studied in detail in the Borkum Reef Ground. The expedition maintained the established methodological framework, combining SCUBA-based video transects and BRUV deployments with sediment core incubations to determine the effects of trawling-induced disturbance on nutrient fluxes, oxygen dynamics, and benthic–pelagic coupling. Landers were again deployed to record current velocities, temperature, salinity, and nutrient concentrations near the seafloor, complementing the sediment core data. Hydroacoustic surveys using SSS, MBES, and SBP refined existing seafloor maps, revealing geomorphological features such as ripples, trawl marks, and sedimentary structures that are key to understanding the spatial variability in benthic community composition and ecosystem processes. These datasets provided updated information crucial for designing the subsequent HE659 cruise and for integrating observations across temporal scales.

HE659, conducted from April 14 to 29, 2025, extended this observation series and expanded the sampling design to include additional control areas outside the designated MPAs. This was a response to the delayed implementation of the fishery exclusion regulations (summer 2023) and allowed for a broader comparison of protected, moderately disturbed, and heavily trawled sites. The expedition pursued the same multidisciplinary strategy, combining biological, geochemical, and physical measurements to assess the cumulative impacts of bottom-contact fishing and the first signs of benthic recovery following protection

measures. SCUBA-based video transects, BRUV deployments, and ARMS installations were used to monitor the structure and diversity of benthic epifaunal communities and the development of sessile assemblages over time. Sediment core incubations focused on quantifying nutrient fluxes and measuring potential rates of bioturbation and bioirrigation under varying disturbance regimes. Multiple benthic landers were deployed, both from HEINCKE and in collaboration with the research vessel SENCKENBERG, to monitor near-bottom hydrodynamics, nutrient dynamics, and the formation of dredging plumes or trawl traces in real time. High-resolution hydroacoustic mapping using SSS, MBES, and SBP provided detailed information on seafloor morphology and substrate heterogeneity, supporting accurate station selection and the interpretation of observed biological and chemical gradients.

Together, the HE602, HE642, and HE659 cruises form a coherent dataset spanning three years of consecutive observations, representing one of the most comprehensive multidisciplinary studies on the ecosystem effects of bottom-contact fishing in the German North Sea. The combination of advanced acoustic seafloor mapping, experimental sediment biogeochemistry, and direct biological observations enables a holistic understanding of how trawling intensity, substrate type, and hydrodynamic conditions interact to shape benthic community structure and ecosystem functioning. Moreover, by linking these data across temporal scales, the series contributes valuable information to evaluate the effectiveness of fishery exclusion zones in achieving the objectives of the European Marine Strategy Framework Directive (MSFD) and the national MPA management plans. The integrated research approach developed through these missions, merging in-situ experimentation, non-invasive observation methods, and cross-disciplinary data analysis, will provide a robust foundation for long-term monitoring and management of North Sea benthic ecosystems under changing environmental and anthropogenic pressures.

Scientific Output

Cruise reports

HE659: https://doi.org/10.48433/cr_he659

HE642: https://doi.org/10.48433/cr_he642

HE602: https://doi.org/10.48433/cr_he602

HE604 and HE625

Ecological long-term observation of benthic communities in the German EEZ of the North Sea

Authors

Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany

J. Beermann, L. Gutow, B. Glückselig, M. Stadler

Federal Ministry for Nature Conservation | Isle of Vilm, Germany

K. Heinicke

The wide structural and functional diversity of benthic organisms and communities makes them sensitive indicators for environmental change (e. g. Shojaei et al. 2016). Extensive research effort is being made to understand the responses of benthic habitats and communities to environmental change and to assess the usefulness of various numerical multivariate indices based on benthic community composition (Borja et al. 2011; van Loon et al. 2018), in order to evaluate the ecological status of marine ecosystems. The increasing understanding of the structure and functioning of benthic communities provides important tools to test the usefulness and efficiency of modern measures of marine management and conservation.

Accordingly, benthic habitats and communities are intensively used as proxies for the assessment of the environmental status according to several European directives and regional marine conventions. Long-term observations on the development of species populations in particular help to understand the implications of ongoing environmental changes and support the development of new indicators of the environmental status of biotopes and ecosystems. The Federal Republic of Germany is obliged to regularly assess and evaluate the status of the benthic communities in its territorial waters. Within a series of past, ongoing and future research projects in cooperation with the German Federal Agency for Nature Conservation (BfN), the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) conducts long-term monitoring programs as

well as specific targeted investigations on benthic habitats, species assemblages and populations to (1) fulfil the requirements of relevant legislative directives and conventions for the German Exclusive Economic Zone (EEZ) and (2) to evaluate the efficiency of specific conservation and management measures. In particular, the European Habitats Directive, the Marine Strategy Framework Directive (MSFD, directive 2008/56/EG), and the Oslo-Paris Convention (OSPAR) provide the framework for the investigations conducted in these projects.

During the cruises HE604 and HE625 of RV HEINCKE, benthic communities were investigated in the German Exclusive Economic Zone (EEZ) of the North Sea. The samplings of the in- and epifauna were conducted in the central EEZ as well as at the on the Dogger Bank and in the Sylt Outer Reef, which are protected areas according to the European Habitats Directive. A newly initiated long-term monitoring program targeted broad habitat types in the German Bight. As part of another, established long-term monitoring program, 25 stations were sampled on the Dogger Bank and in the Sylt Outer Reef. Further, samples were taken in the Sylt Outer Reef to investigate the recovery of the benthic ecosystem after cessation of chronic bottom trawling. The in- and epifauna were sampled using a van Veen grab, an epibenthos dredge and a towed underwater video system. Further, the sampling methods are continuously refined, improved and complemented by new monitoring tools and analyses.

Building on established monitoring programs, the collected data allow for the elucidation of spatiotemporal dynamics of benthic communities and the delimitation of protected habitat types, supporting the fulfillment of national sovereign duties of the Federal Republic of Germany to implement the EU MSFD as well as the EU Habitats Directive.

References

- Borja A, Barbone E, Basset A, et al., Response of single benthic metrics and multi-metric methods to anthropogenic pressure gradients, in five distinct European coastal and transitional ecosystems, *Marine Pollution Bulletin* 2011, 62, 499–513, <https://doi.org/10.1016/j.marpolbul.2010.12.009>.
- van Loon WMGM, Walvoort DJJ, Hoey G, et al., A regional benthic fauna assessment method for the Southern North Sea using Margalef diversity and reference value modelling, *Ecological Indicators* 2018, 89, 667–679, <https://doi.org/10.1016/j.ecolind.2017.09.029>.
- Ghodrati Shojaei M, Gutow L, Dannheim J, Rachor E, et al., Common trends in German Bight benthic macrofaunal communities: assessing temporal variability and the relative importance of environmental variables, *Journal of Sea Research* 2016, 107, 25–33, <https://doi.org/10.1016/j.seares.2015.11.002>.

Scientific Output

List of Publications

Bonthond G, J Beermann, L Gutow, A Neumann, et al., Benthic microbial biogeographic trends in the North Sea are shaped by an interplay of environmental drivers and bottom trawling effort, ISME Communications 2023, 3 (132), doi: 10.1038/s43705-023-00336-3.

Ebbe B, M Gusky, J Beermann, K Heinicke & L Gutow, First sighting of *Streptosyllis nunezi* (Polychaeta: Syllidae) in the German Bight, SE North Sea, Journal of the Marine Biological Association of the UK 2024, 104 (e77), doi: 10.1017/S0025315424000663.

List of conference presentations

2025 | **Biodiversity monitoring in the southeastern North Sea: identification and characterization of threatened benthic biotopes** One Ocean Science Congress, Nice, France.

2025 | **First insights of a new reef area in the muddy biotope of the northeastern Elbe paleo river** Marine Conservation Colloquium, Vilm, Germany.

2024 | **Detection und characterization of protected seafloor biotopes in the North Sea using underwater video systems** Marine Conservation Colloquium, Vilm, Germany.

Data

Continuous thermosalinograph:
<https://doi.pangaea.de/10.1594/PANGAEA.972855>

Cruise Reports

HE604: https://doi.org/10.48433/cr_he604

HE625: https://doi.org/10.48433/cr_he625

HE605

The role and range boundaries of gelatinous zooplankton in the rapidly changing Arctic marginal seas

Authors

University of Bremen | Bremen, Germany
C. Havermans

Cruise summary

The HE605 expedition “RISING” with R/V Heincke aimed to characterize zooplankton communities in fjords and open ocean, along a poleward latitudinal gradient, from Northern Norway to Svalbard. The main focus of the cruise was the study of gelatinous zooplankton (cnidarian medusae, ctenophores and pelagic tunicates), investigating their species diversity, distribution patterns, ecological role and adaptation potential. By comparing Arctic and Atlantic fjords influenced by distinct water regimes, the obtained data laid a solid baseline of gelatinous zooplankton diversity and distributions. Comparing Arctic vs. Atlantic community compositions allowed us to better predict climate-change driven poleward range shifts of Atlantic zooplankton species under ongoing environmental changes. In Svalbard, we visited five western Svalbard fjords, of which the degree of Atlantic influence differed: Krossfjorden, Kongsfjorden, Billefjorden, van Mijenfjorden and Hornsund. On the way south to mainland Norway, we sampled at three localities in the open Barents Sea. Thereafter, we sampled in various localities in Porsangerfjorden, northern Norway, and on the borders of the Bleik Canyon near Andøya. Scientific deployments included the CTD/rosette water sampler to measure physical properties of the water column and sample water for environmental (eDNA analyses), the Van Veen Grab to collect sediment for eDNA analyses, plankton nets to collect zooplankton and small nekton (Bongo, WP3 and Multi-nets), scientific angling for fish, and optical video platforms including the Pelagic In-situ Observation System PELAGIOS, the Ocean Floor Observation System OFOS and a BlueROV2 equipped with underwater cameras. During the expedition, more than 2000 zooplankton samples were collected for morphological, molecular, biomarker and contaminant analyses, 114 sediment

samples and 518 filters for eDNA analyses, and over 14 hours of video footage was recorded for in-situ observations of gelatinous and other organisms. These samples and data are currently being analyzed in the context of different projects under the umbrella of the Helmholtz Young Investigator Group ARJEL at the AWI, and ongoing research projects at GEOMAR and the University of Bergen.

Objectives

The overarching goals of this expedition were to obtain a baseline of gelatinous zooplankton (GZP) diversity, abundance and distribution and link these to local water masses. This was achieved along a latitudinal gradient, and in fjords with a different degree of Atlantic vs. Arctic water mass influence, as well as along a vertical (depth) gradient. We applied an integrative survey combining plankton net catches with modern technologies in optics together with state-of-the-art molecular analyses to realize the following objectives:

- Obtain species inventories and abundances of GZP and other planktonic and nektonic species;
- Reveal the molecular diversity of species encountered in different water masses, regions and depths and evaluate the genetic connectivity between regional populations of dominant species;
- Characterize local species boundaries across environmental gradients (Atlantic vs Arctic water masses, surface to deep) of GZP to better understand their habitat preference;
- Identify the efficiency of environmental DNA (eDNA) to characterize zooplankton communities over spatial and temporal scales;
- Elucidate the trophic role of GZP in regional food webs, as predator, and as prey for fish species;
- Evaluate the importance of jellyfish carcasses as vectors for carbon, linking pelagic and benthic food webs;
- Assess the role of jellyfish and other zooplankton as vectors for microplastics and, potentially, other contaminants;
- Investigate the occurrence of parasitism in (semi)-GZP such as scyphozoans, hydrozoans, and chaetognaths;
- Evaluate the response of dominant zooplankton to stressors.

Main findings

In-situ Observations

We analyzed the *in-situ* observations from the towed pelagic camera system PELAGIOS and the benthic camera system OFOS to assess the diversity and vertical distributions of gelatinous zooplankton in the fjords visited as well as the offshore sites in the Barents Sea (Pantiukhin et al. 2024). We recorded more than 1000 individual observations of gelatinous zooplankton, which could be assigned to fourteen taxonomic groups, of which the most dominant were the hydrozoan *Aglantha digitale*, and the ctenophores *Beroe* spp., and *Bolinopsis infundibulum*. We found that transformed Atlantic water masses harbored the highest gelatinous zooplankton abundance, while intermediate waters showed the highest species richness. This supports previous studies (e. g., Pantiukhin et al. 2023) in which Atlantic water masses were associated with the highest gelatinous zooplankton abundances. So far undocumented dense aggregations of the Nuda ctenophore *Beroe* spp. were recorded in Van Mijenfjorden in Svalbard as well as aggregations of the lobate ctenophore *Bolinopsis infundibulum* in the open Barents Sea, with, for the latter species, over 2.67 individuals per cubic meter at a water depth of 100 m. Other recorded taxa with PELAGIOS included the hydrozoans *Aglantha digitale*, *Melicertum octocostatum*, *Solmundella bitentaculata*, Pandeidae sp. and Physonectae spp., the scyphozoan *Cyanea capillata* and the ctenophores *Mertensia ovum* and *Euplokamis* sp. The observed distribution patterns during HE605 (published in Pantiukhin et al. 2024) may provide a baseline for future monitoring efforts of gelatinous zooplankton distributions. The documented gelatinous zooplankton aggregations during HE605 showed a clear zonation with depth, and probably may have extended over many kilometers, however, the spatial extent remains uncertain and further investigations with similar towed underwater video systems should shed light on the physical features influencing them.

Morphological studies

A selection of >250 net-caught specimens representing most cnidarian and ctenophore species observed during the expedition were individually documented for morphology alive with a camera attached to a stereomicroscope and/or macrophoto prior to fixation in 99% ethanol for molecular work. The samples are currently being used for DNA barcoding of COI and 16S sequences with photographic vouchers, a major effort led by the University of Bergen and the HYIG ARJEL at the AWI. Sequences obtained will be made openly accessible in reference sequence databases. Collected morphological and molecular data are currently also being used to resolve existing taxonomic questions. A total of >35 taxa of ctenophores and cnidarians were observed during the cruise. *Beroe* spp. ctenophores include both morphotypes *B. cf. cucumis* and *B. cf. abyssicola*, the taxonomy of which is currently uncertain. A ctenophore specimen belonging to a genus pending description (Majaneva, Hosia et al., unpublished results) was

also collected at van Mijenfjorden. Highest densities were found at station 27 in Porsangerfjorden, where there were abundant physonect siphonophores and numerous *Clytia* sp., as well as at Hornsund, with abundant *Aglantha digitale*. *A. digitale* was the only species observed at all stations, while *Beroe* spp. were observed on all stations except for two in Porsangerfjorden. The species count (not normalized for sampling effort) increased towards the southern stations, with the Porsangerfjorden area having the highest total number of species. Pronounced environmental gradients along the fjord likely contributed to this diversity, with the resulting change in community composition from station to station. The outermost station at Porsangerfjorden and the Vesterålen stations were characterized by large numbers of siphonophores, particularly physonects. Many detached physonect nectophores in these stations poses a challenge to estimating abundances. Predominantly Arctic species were observed in Billefjorden, van Mijenfjorden, Hornsund, and in the Barents Sea. In addition to several species of hydromedusae with Atlantic affinities, Tomopteris polychaetes and collodarian radiolaria were observed in the Barents Sea, Porsangerfjorden and Vesterålen, while doliolids were found in the outer station at Porsangerfjorden and in Vesterålen, indicating a more Atlantic influence in these areas. Further analyses will combine the community composition and abundance data from the net samples with temperature and salinity data from the CTD to investigate more in detail the associations of the gelatinous fauna with Arctic and Atlantic water masses within the study area.

Environmental DNA

A total of 31 CTD casts were carried out, and the filtering of the collected seawater resulted in 518 Sterivex filters for eDNA analyses. From the 49 Van Veen Grab deployments, 114 sediment samples were obtained for eDNA analyses. In the AWI home laboratories, DNA has so far been extracted from these >500 filters and from 50% of the sediment samples. PCR amplification has and will be performed with triplicates using a set of universal primers and taxon-specific ones, depending on the study area. The general primers include those targeting the v1-2 region of 18S rRNA and primers targeting a 313-bp fragment (the commonly used “Leray fragment”) of the cytochrome c oxidase subunit I (COI) gene. The eDNA samples from Bleik Canyon and the Barents Sea have already been sequenced for COI on a NovaSeq Illumina sequencer. Further samples will also be sequenced later this year (2025). Once all samples have been extracted PCR amplification will be performed with triplicates on these samples and bioinformatic analyses will allow us to investigate patterns of distribution at the scale of Metazoa.

In Porsangerfjorden, we also carried out an eDNA case study addressing the reliability of eDNA water sampling methods and the temporal variation of eDNA in the water column. The aim was to find out i) if and how the metazoan community composition across the water column varies in a time span of a couple of hours as well as between specific depths, and ii) if one CTD/rosette sampler deployment

can comprehensively identify the local metazoan diversity in a dynamic fjord system. We used the Leray COI fragment and Illumina MiSeq sequencing platform to obtain this dataset. The comparison of communities and dominant metazoan species, including gelatinous zooplankton revealed differences in spatial and temporal variation (Gorniak et al. in prep). A similar study will be carried out on eDNA from sediment sampling across small spatial scales.

Trophodynamics

A study on the regional variation in diet of Atlantic cod (*Gadus morhua*) including biomarker analyses combined with DNA metabarcoding of stomach contents has been submitted and is currently under review (Dischereit et al.). Further molecular diet and biomarker studies are currently in progress.

References

Pantiukhin D, Verhaegen G, Kraan C, Jerosch K, Neitzel P, Hoving HJT & Havermans C, Optical observations and spatio-temporal projections of gelatinous zooplankton in the Fram Strait: a gateway to a changing Arctic Ocean, *Frontiers in Marine Science* 2023, 10, 987700, doi:10.3389/fmars.2023.987700.

Pantiukhin D, Soto-Angel JJ, Hosia A, Hoving HJ & Havermans C, In-situ observations of gelatinous zooplankton in inshore and offshore Arctic waters, *Polar Biology* 2024, 47, 1575–1592, doi:10.1007/s00300-024-03306-0.

Scientific Output

List of Publications

Pantiukhin D, Soto-Angel JJ, Hosia A, Hoving HJ & Havermans C, In-situ observations of gelatinous zooplankton in inshore and offshore Arctic waters, *Polar Biology* 2024, 47, 1575–1592, doi:10.1007/s00300-024-03306-0.

List of conference presentations

2023 | **Integrative pelagic studies for assessing diversity, distributions, trophic role and range shifts of jellyfish in Tomorrow's Arctic Ocean** ASLO meeting, Palma de Mallorca, Spain.

2023 | Assessing short-term temporal variation of metazoan environmental DNA in a fjord system (Porsangerfjorden, Norway) to test a commonly used water sampling strategy ASLO meeting, Palma de Mallorca, Spain.

2023 | More jellyfish in Tomorrow's Arctic Ocean? Integrative pelagic studies for predicting poleward range shifts and their potential impact on Arctic food webs and fish stocks Arctic Science Summit Week, Vienna, Austria.

2023 | Integrative pelagic studies for assessing diversity, distributions, trophic role and range shifts of jellyfish in Tomorrow's Arctic Ocean Nansen Legacy Symposium, Tromsø, Norway.

2023 | Integrative pelagic studies for assessing diversity, distributions, trophic role and range shifts of jellyfish in Tomorrow's Arctic Ocean Svalbard Science Conference, Oslo, Norway.

Data

Master track:

<https://doi.org/10.1594/PANGAEA.950690>

Thermosalinograph data:

<https://doi.org/10.1594/PANGAEA.963419>

Phys. oceanography (raw data):

<https://doi.pangaea.de/10.1594/PANGAEA.966885>

Physical oceanography (CTD):

<https://doi.org/10.1594/PANGAEA.961713>

Cruise Report

HE605: https://doi.org/10.48433/cr_he605

HE611

Baltic Sea and North Sea Cruise HE611

Authors

Hereon Helmholtz Centre | Geestacht, Germany

H. Thomas

and HE611 scientific party



Figure 1: RV Heincke.

The HE611 expedition with the RV Heincke from November 4 to December 1, 2022 aimed to investigate the exchange between atmospheric, oceanic, and sedimentary carbon reservoirs in the North Sea and Baltic Sea during the winter months. Particular attention was paid to a synoptic view of both seas in order to better quantify the role of the Baltic Sea outflow for the carbon system of the North Sea. Furthermore, the expedition aimed to close the research gap in the North Sea and Baltic Sea, focusing on the pelagic and benthic processes that control the carbon sink in coastal waters. To this end, a comprehensive, interdisciplinary sampling and measurement program was implemented, linking physical, chemical, and biogeochemical components.

An essential part of the measurement program was a $1^{\circ} \times 1^{\circ}$ grid in the North Sea as well as selected transects and stations in central areas of the Baltic Sea, particularly in the Gotland, Arkona, and Bornholm basins and along the German coast. Extensive water samples were taken to determine temperature, salinity, nutrients, oxygen, $p\text{CO}_2$, trace gases, and carbon parameters. This was supplemented by sediment samples at selected stations, which are intended to provide information about exchange processes at the sediment-water interface.

At the same time, continuous measurement systems were running on board. During the voyage, the FerryBox recorded basic hydrographic parameters such as temperature, salinity, chlorophyll fluorescence, turbidity, and oxygen. It was also equipped with a $p\text{CO}_2$ sensor. The data show clear spatial gradients, especially when crossing the Skagerrak, which differed significantly from measurements taken a year earlier due to different meteorological conditions. This variability underscores the importance of wind regimes and water mass transport for the regional carbon system.

Another methodological focus was on eddy covariance (EC) measurements of air-water CO_2 exchange. Sensors installed on the foredeck – including a 3D ultrasonic anemometer, motion sensors, GPS, and a CO_2 analyzer – enabled continuous high-resolution flux measurements. The system operated largely without disruption; daily data backup ensured a complete data set for later analysis. Extensive data processing (motion correction, calibration, coupling with water-side data) is being carried out in collaboration between Hereon and GEOMAR.

To supplement the EC measurements, a marine X-band radar was operated, which continuously provided information on sea conditions and thus supported the interpretation of CO_2 fluxes. In addition, a large number of water samples were taken during the expedition. In addition to dissolved greenhouse gases and dissolved organic matter, radium isotopes, carbonates, and trace metals were also examined and analyzed.

A multicorer was used to collect virtually undisturbed samples of surface sediments. Several sediment samples containing pore water were obtained at the sites and made available for various investigations. Individual, specially prepared sediment samples were examined for later measurement of nutrients and dissolved metals in pore water. A second set of samples was cut into slices for later analysis of particulate metals, C/N analysis, TEP analysis, and chlorophyll content. A third set of cores was subjected to an incubation experiment with whole cores to directly measure benthic fluxes of oxygen, nutrients, metals, DIC/AT, and greenhouse gases.

However, the expedition was significantly affected by persistent stormy weather. Multiple route adjustments were necessary, which meant that the northernmost

areas of the North Sea in particular could not be sampled as planned. Instead of starting in the North Sea as planned, the voyage first had to proceed via the Kiel Canal to the Baltic Sea. In addition, weather-related interruptions in Warnemünde, Bremerhaven, and Hirtshals led to time constraints.

Despite the meteorological challenges, significant parts of the scientific program were successfully implemented. The hydrographic, biogeochemical, and flux-based measurement data obtained provide a valuable basis for assessing winter carbon dynamics in the North Sea and Baltic Sea. In particular, the combination of point samples, continuous surface data, and direct flux measurements provide new insights into the variability of carbon exchange processes and their controlling factors. The data are an important contribution to future modeling and to understanding the role of regional marginal seas in the European carbon cycle.

Scientific Output

Data

Cruise data:

<https://doi.pangaea.de/10.1594/PANGAEA.956785>

Cruise report

HE611: https://doi.org/10.48433/cr_he611

HE621

Comparison of Modelling and Measurements of GI-Source Sound Propagation in the North Sea

Authors

Federal Institute for Geosciences and Natural Resources (BGR) | Hannover, Germany

M. Engels, M. Breitzke, M. Schnabel, B. Schramm, A. Ehrhardt

Introduction

Cruise HE621 was an instrument test survey with two working days. At two locations in the German North Sea, we recorded the sound emissions of two airguns (GI-Source by SERCEL) along several profiles, using three broadband hydrophones at different depths in the water column below a buoy and anchored on the seafloor. These results are compared with theoretical sound propagation modelling at the same location, which has been carried out in 2021 by DHI WASY GmbH for BGR.

Experiment setup

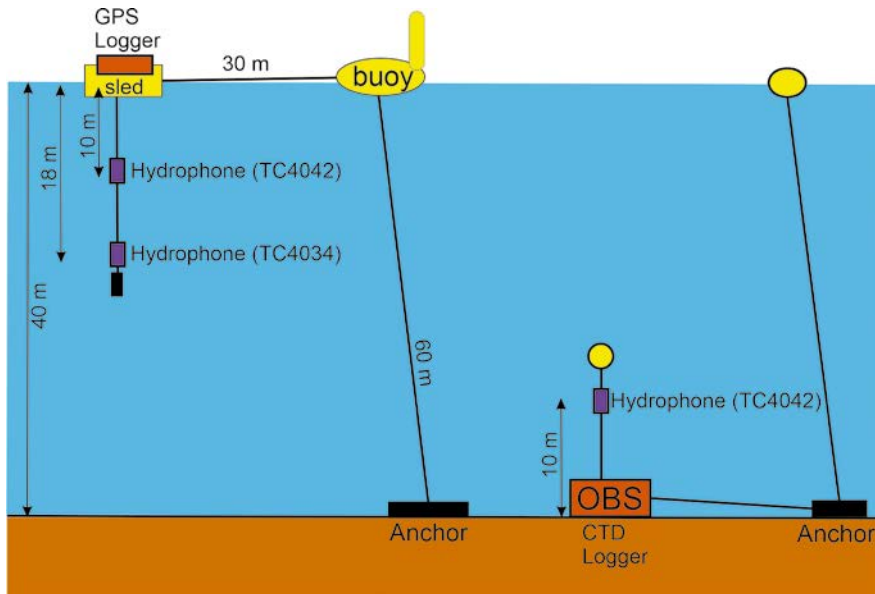


Figure 1: Measurement set-up: Two hydrophones recorded at 10 m and 18 m water depth attached below a floating sledge (with GPS and two data loggers), which was connected with an anchored seismic end buoy. One hydrophone recorded at 30 m water depth attached above an OBS (with CTD and data logger). The OBS is attached to an anchor, which can be recovered via a buoy.

The developed measurement setup to be tested by this cruise consisted of a buoy, which was anchored at the target coordinate (38 m water depth), carrying two hydrophones (TC4042 & TC4034 by Teledyne RESON) which were fixed along a line at 10 m and 18 m below sea level. In addition, another hydrophone (TC4042) was floating 10 m above an ocean bottom mooring (Lobster type) using a buoy. The two different types of hydrophones covered a frequency range of a few Hz to 400 kHz, recorded by two different loggers for the first time: Keysight DAQ70A with DAQM909A sampling at 800 kHz and the ocean bottom seismometer (OBS) logger 6D6 by KUM sampling at 4 kHz. The source were two GI-sources in true GI-mode (generator 45 in³, injector 105 in³), 150 bar air pressure was provided by a rented compressor (WP4341 by Sauer & Sohn).

Due to strong wind and swell conditions, it was not possible to work in the planned target area during the first working day. Instead, test profiles were recorded in the lee of Heligoland, until the increasing swell forced us to stop the measurements at this location. On the second working day, with gradually improving weather, the sound pressures of different airgun configurations were recorded along several profiles at the planned target site (6.303 °E, 54.644 °N, German EEZ).

Results of GI-source calibration

Metrics: After applying hydrophone and logger calibrations, we receive time series of pressure in Pascal [Pa], which were bandpass filtered. We computed for each shot (one per minute) the sound pressure level peak to peak SPL_{pp} and zero to peak SPL_{zp} [dB re 1 μ Pa] from the wave train of multiple reflected waves within the water layer and refracted waves through the sediments. The direct wave is canceled out in the shallow sea after a few hundred meters due to the Lloyd's Mirror Effect (e. g. Erbe, 2011). Furthermore, time series of power SPL_{rms} [dB re 1 μ Pa²] and sound exposure level SEL [dB re 1 μ Pa²s] have been computed for each shot. SEL is a measure for the sound energy computed from an interval containing 90% of the pulse energy and normalized to 1 s (e. g. Erbe, 2011).

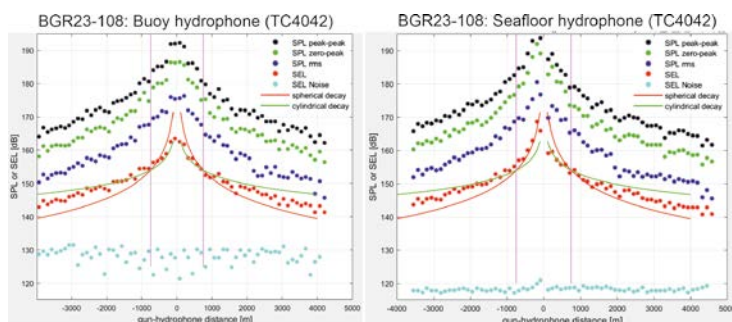


Figure 2: SPL and SEL values (coloured stars) for each one-minute shot along profile BGR23-108 (negative distances are approach, positive distances departure). The buoy hydrophone (left panel) was attached 10 m below sea surface and the seafloor hydrophone (right panel) 10 m above the seafloor (28 m water depth). For the SEL values in red, cylindrical and spherical decay are indicated by a green and red solid line, respectively. The vertical magenta line is at 750 m source-hydrophone distance.

Law of decay: Profiles BGR23-105 and BGR23-108 on the second day at the target location (38 m water depth) in the EEZ operated with two GI-sources at 155 bar. The decay of SEL with increasing distance R varies between cylindrical ($10 \log R$) and spherical ($20 \log R$). Linear regression over log distance achieved a decay law around $15 \log R$ (scattering between $13 \log R$ and $16 \log R$ for the two profiles for approach and departure).

During day 1 in the lee of Heligoland with Bf 6 to 7 and a shallower water depth of 28 m, the decay is even faster than spherical (around $25 \log R$). The rough sea surface is a bad reflector and therefore, the multiple reflections between seafloor and sea surface decay faster with distance. In agreement, also the SEL level at 750 m distance is 5 dB lower during day 1.

SEL: Differences between the hydrophones below the buoy and the hydrophone at the seafloor are small with a tendency to a faster decay of the seafloor

hydrophone. The SEL values at 750 m distance are close to 155 dB re 1 $\mu\text{Pa}^2\text{s}$ well below the BSH regulation limit for pile-driving wind farm construction (Müller & Zerbs, 2011) of 160 dB re 1 $\mu\text{Pa}^2\text{s}$ at 750 m distance (see also ‘Schallschutzkonzept’ of Bundesministerium für Umwelt, 2013). During approach, the sound level is slightly lower than during departure due to the shadow effect of the vessel between source and receiver.

Background noise: The SEL noise level below the buoy close to the rough sea surface recorded during the gap between shots scatters around 130 dB re 1 $\mu\text{Pa}^2\text{s}$, while the SEL noise level recorded close to the seafloor is stable around 118 dB re 1 $\mu\text{Pa}^2\text{s}$. The clashing waves and the up and down movements of the hydrophone below the buoy may contribute to the higher hydrophone noise level, while the stable seafloor hydrophone is recording a more realistic noise level for Bf 5. The vessel noise was only visible by the seafloor hydrophone when sailing directly above it by an increase close to 130 dB re 1 $\mu\text{Pa}^2\text{s}$.

GI-source modes: The comparison of a single versus two GI-sources yields the expected difference of ~3 dB SEL (energy doubling). A profile with a single GI-source shooting with generator only (without injector) yields very similar sound pressures compared to the true GI-source mode, indicating that the injector for reducing the bubble does not increase the sound emissions; the primary generator volume is the relevant volume.

Comparison with Modelling

A contract study of DHI WASY GmbH (Stöber et al., 2021) was modelling the sound propagation of 2 GI-sources in the shallow North Sea. The modelling in the frequency domain includes water column (CTD profiles) and seafloor properties (earth model) for sound propagation including losses. Furthermore, cumulated sound emissions SELcum have been modelled for static and moving mammals and compared with German and NOAA (USA) regulations.

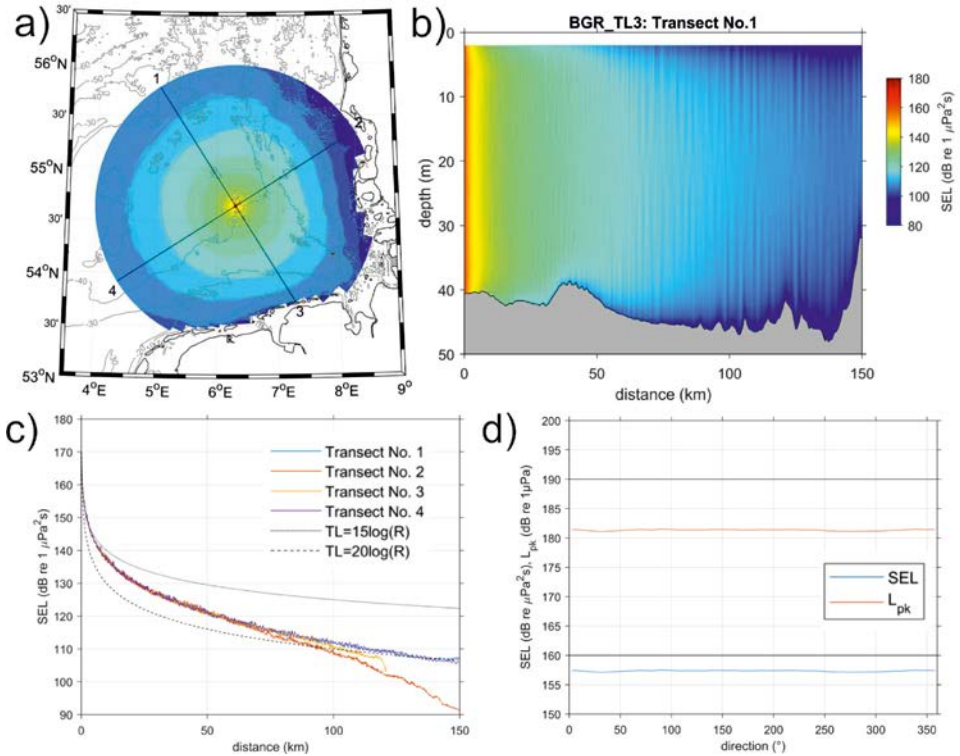


Figure 3: **a)** Modelling area, **b)** SEL propagation along transect 1 towards NW, **c)** SEL decay with distance along four transects (in colour) and black solid line as $15 \log(R)$ reference, **d)** SEL (blue) and SPL (orange) at 750 m distance for all azimuths (limits at 190 dB for SPL and 160 dB for SEL are indicated as solid black lines).

The modelling of SEL has been conducted up to 150 km distance. In the short range up to 5 km the decay follows the transmission loss of $15 \log R$. This decay has been confirmed by the measurements during this cruise along the 4 km profiles. For larger distances up to ~50 km, modelling is close to a spherical decay and at larger distances, the decay is even faster than spherical due to increasing transmission losses.

The German SPL and SEL limits (BSH regulations for wind farm pile constructions) are complied by modelling and measurements: Instead of the limit of $SPL_{pp} = 190$ dB re $1 \mu Pa$, modelling yields 181,3 dB re $1 \mu Pa$ and this is confirmed by HE621 measurements; instead of the limit of $SEL = 160$ dB re $1 \mu Pa^2 s$ modelling yields 157,3 dB re $1 \mu Pa^2 s$ compared to 155 dB re $1 \mu Pa^2 s$ by HE621 measurements (with a 1 dB scattering).

Thus, the reliability of theoretical modelling has been confirmed by GI-source sound measurements. Sound emissions are well below regulation limits, the conservative modelling assumptions yields slightly larger SEL values than the

real measurements. The knowledge of the decay law in the shallow water case allows better predictions of sound propagation levels in ranges which are typically observed by marine mammal observers and can be used for modelling of other sources (e. g. by Gundalf software).

References

Erbe C, Underwater acoustics: Noise and the effects on marine mammals, A pocket handbook 3rd edition, JASCO Applied Sciences 2011.

Müller A & Zerbs C, Offshore-Windparks: Messvorschrift für Unterwasserschallmessungen, Auftraggeber: Bundesamt für Seeschifffahrt und Hydrographie (BSH) 2011.

Stöber U, Brandt J, Müller A, Zerbs C & Samocinska-Kot J, Modellierung der Unterwasserschallemission wissenschaftlicher Sonare und seismischer Quellen für Umweltverträglichkeitsstudien, BGR Auftragsvergabe an DHI WASY GmbH, 2021.

Scientific Output

List of Publications

Engels M, Breitzke M, Schnabel M, Schramm B, Ehrhardt A, Stöber U, Müller A, Zerbs C, et al., Calibration and Modelling of GI-gun Underwater Sound in the Shallow Water Case of the North Sea, in preparation for J. Acoust. Soc. Am.

Data

Master track (1s resolution):
<https://doi.pangaea.de/10.1594/PANGAEA.962866>

Hydroacoustic data:
BSH Online-Portal MarinEARS
<https://www.marinears.bsh.de> (ongoing) & BGR archive servers

Cruise Report

HE622, HE635 and HE655

Legacies of war – assessment of munition hotspots in the German Bight

Authors

**Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research |
Bremerhaven, Germany**
M. Brenner

GEOMAR Helmholtz Centre for Ocean Research | Kiel, Germany
J. Greinert

Millions of tons of munitions from the First and Second World War are littering the North Sea. They were lost during battles, still on board of ships at the time of their sinking, or dumped after the Wars. Within the German portions of the North Sea and Baltic Sea alone contain some 1.6 million metric tons of munitions, with 300 000 tons in the German Baltic and around 1.3 million tons in the German part of the North Sea (Böttcher et al. 2011). The distribution and condition of munitions in German waters are not well known, and in addition to the explosion and security risk, these munitions contain toxic chemicals.

One of the most important substances in this context is 2,4,6-trinitrotoluene (TNT). Used commonly as an explosive for military applications, it is known for its toxicity and to be mutagenic and carcinogenic. In the marine environment, corrosion ultimately results in the leakage of TNT from underwater munitions, affecting the surrounding sediments and biota (e. g. Koske et al. 2020, Maser et al. 2023 & Kammann et al. 2024), and potentially accumulating in the food web. As consequence, there is growing interest in remediating undersea munitions due to the ecological and human health risks and the hazards associated with dredging and increasing development of offshore infrastructure associated with aquaculture, wind farms, cables, and oil or gas pipelines, and increasing ship traffic in general.

In the German parts of the Baltic Sea dumped munition is found close to the coast in relatively shallow waters (Böttcher et al. 2011). Most of the munition is laying on the sediments, making it relatively easy to map and identify the munitions as well as to assess their condition. In contrast, the munition in the North Sea is buried

today under migrating sand dunes e. g. at dumping sites north of the Frisian islands or was deliberately covered with harbor sediments like the dump site Minsener Oog and Hooksielplate in the Jade estuary (Figure 1). Like this, estimates of the amount and condition of the remaining munitions are difficult. Further, sand coverage is also deadening the emissions from the leaking explosives necessitating the adaptation of e. g. analytical methods to trace explosives chemicals in both sediment and surrounding waters.



Figure 1: Map of the southern German Bight of the North Sea showing the dump sites for conventional munition nördlich Spiekeroog and Hooksielplate in the Jade estuary. In addition, the only dump site for chemical warfare agents Tiefe Rinne south of Helgoland is shown.

Within the frame of the projects CONMAR and REMARCO RV Heincke cruises HE622, HE635 and HE655-2 were conducted to investigate the dump sites Nördlich Spiekeroog, Steingrund und westlich Sylt for conventional munitions and Tiefe Rinne for chemical warfare agents. In addition, also war wrecks still containing munition, such as the SMS Ariadne, Vigo and SMS Hela were visited.

Aims of the cruises were to map the dump sites and wrecks according to their bathymetry and magnetometry, to trace dissolved explosives in sediment and surrounding waters and to investigate microbial and infauna communities as well as bottom dwelling fish species regarding the impact of dissolved explosives on community structure and health of the investigated organisms.

In addition, a remote operating under water crawler, equipped with revolving water sampler and sediment sampling device was developed and tested for its abilities as a monitoring tool able to sample video controlled from the inner part of a dump site and around a wreck.

References

Böttcher C, Knobloch T, Rühl N-P, Sternheim J, Wichert U, & Wöhler J, Munitionsbelastung der deutschen Meeresgewässer – Bestandsaufnahme und Empfehlungen (Stand 2011), Hamburg: Bundesamt für Seeschifffahrt und Hydrographie 2011, 177 pp.

Koske D, Straumer K, Goldenstein, N I, Hanel R, Lang T & Kammann U, First evidence of explosives and their degradation products in dab (*Limanda limanda* L.) from a munition dumpsite in the Baltic Sea, *Marine Pollution Bulletin* 2020, 155, 111131, <https://doi.org/10.1016/j.marpolbul.2020.111131>.

Strehse JS, 1, Bünning TH, Koschorreck J, Anita Künitzer A & Maser E, Long-Term Trends for Blue Mussels from the German Environmental Specimen Bank Show First Evidence of Munition Contaminants Uptake, *Toxics* 2023, 11, 347, <https://doi.org/10.1016/j.marpolbul.2020.111131>.

Kammann U, Töpker V, Schmidt N, Rödiger M, Aust MO, Gabel M & Scharsack JP, Explosives leaking from dumped munition contaminate fish from German coastal waters: a reason for chronic effects?, *Environmental Sciences Europe* 2024, 36, 116, <https://doi.org/10.1186/s12302-024-00942-5>.

Scientific Output

List of Publications

Zander TJ, 2023, Munition Compound Concentrations in Waters of the German North Sea, Bachelor thesis, University of Hamburg, 33 pp.

List of conference presentations

2025 | **Explosive legacies: Revealing wartime TNT pollution in the North Sea through Bacterial Indicators**, FEMS Micro, Milan, Italy

Data

Tippenhauer, S; Hoppmann, M; Brenner, M (2023): Physical oceanography during RV HEINCKE cruise HE622:

<https://doi.org/10.1594/PANGAEA.963445>

Tippenhauer, S; Hoppmann, M; Brenner, M (2024): Physical oceanography during RV HEINCKE cruise HE635:

<https://doi.org/10.1594/PANGAEA.971598>

Tippenhauer, S; Hoppmann, M; Brenner, M (2025): Physical oceanography during RV HEINCKE cruise HE655/2:

<https://doi.org/10.1594/PANGAEA.982773>

Cruise Reports

HE622 (MecoMM-NS): https://doi.org/10.48433/cr_he622

HE635 (MecoMM-NS II): https://doi.org/10.48433/cr_he635

HE655/2 (MecoMM-NS II.b): https://doi.org/10.48433/cr_he655_2

HE627

FjordChange: Impact of atlantification on ecosystem structure and function in Arctic fjords (Svalbard)

Authors

Alfred Wegener Institute Hemholtz Centre for Polar and Marine Research | Bremerhaven, Germany

U. John, C. Hörstmann, M. Andipalagan, P. Bokowski, M. Fernandez, J. Giesler, N. Kühne, G. Mollenhauer, T. Kanzow

Institute for Chemistry and Biology of the Marine Environment | Oldenburg, Germany

M. Albinus, A. Happe, R. Henkel, J. Matz, D. Voß

Norwegian Institute for Water Research | Oslo, Norway

W. Eikrem

University of Hamburg | Hamburg, Germany

C. Pein

Global change is causing significant environmental shifts in the Arctic. The fjords of Svalbard are increasingly affected by warm, salty water from the North Atlantic (a process known as Atlantification). Additionally, increased glacier melt is leading to greater inflow of freshwater within the fjords. The FjordChange research cruise (HEINCKE HE627) aimed to improve our understanding of the impact of Atlantification on communities and ecosystem processes. The study area includes four fjord systems that are affected to varying degrees by Atlantification: The Van Mijenfjord (south) and the Kongsfjord, which is now ice-free year-round (northwest), are severely affected. In contrast, the Wijdefjord in the north shows significantly less Atlantification, as well as less ice cover in winter. The Rijpfjord (northeast) is influenced by polar water. To understand studies on plankton community diversity and activity in relation to seasonal changes, moorings were installed at the mouths of the Van Mijenfjord and Wijdefjord.

HE627 is the first in a planned series of studies to be conducted over a five-year period. These studies will enable us to analyse the variability of fjord properties in

relation to the influence of Atlantic water from the West Spitsbergen Current, as well as the effect of freshwater inflow.

Two objectives were addressed with the research cruise. Objective 1 aimed for understanding the impact of Atlantification on the physical and chemical oceanography in Arctic fjord ecosystems. (Q1) What is the impact of Atlantic Water and glacial melt water on water mass distribution, stratification, light availability, nutrient concentrations, and input and distribution of dissolved organic matter in the four fjord systems? (Q2) How is lateral nutrient transport from the fjords to the shelf systems affected by inflow and circulation of Atlantic Water within the fjord systems?

Objective 2 aimed for investigating the impact of atlantification on ecosystem structure and function (including assessing the recent and past changes of the eukaryotic and prokaryotic plankton diversity). (Q3) What is the impact of Atlantification on the pelagic community composition and function, from prokaryotes to microplankton? (Q4) Has warming since the industrial changed the biodiversity an associated process?

During the cruise, we took samples of river and glacier runoff, as well as ice samples, in each fjord. These samples should provide information about the influence of glacier melt. The extent of the glacier retreat since voyage HE492 in 2017 was striking. In addition, geological and subsequent paleometagenomic analyses of sediment cores and ancient DNA from sediments (sedaDNA) allow us to analyse changes in communities in Svalbard since industrialisation and trace the drivers of biodiversity change over the last 200 years. Furthermore, we sampled and studied the water column to characterise the oceanography and chemistry within and between the fjords. We used metabarcoding and metatranscriptomic approaches to study biodiversity and community activity via metatranscriptomics. Combining these approaches with analyses along physicochemical gradients from south to north will allow us to predict the future evolution of fjord systems. Ultimately, this should lead to model-based, upscaled estimates of the effects of climate change on pelagic communities, energy transfer in marine food webs, and the performance of the biological carbon pump.

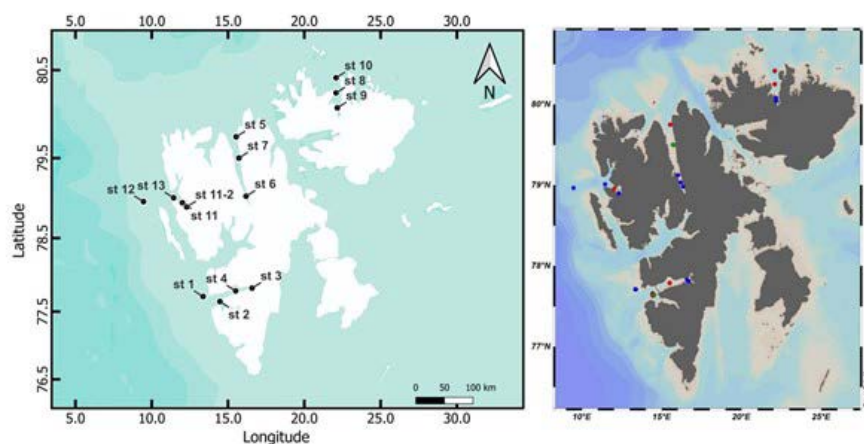


Figure 1: RV HEINCKE cruise HE627. Stations plan with numbers in van Mijenfjorden, Kongsfjorden, Widjefjorden and Rijpefjorden. Blue general sample stations, red MUC station, green moorings.

Scientific Output

List of Publications

Bokowski P, Arctic Fjord Microbial Community dynamics under different degrees of atlantification. Master Marine Biology University of Bremen, defended Oct 2024.

Andipalagan M, Metatranscriptomics and Metabarcoding Analyses of Toxigenic Algal Species in Arctic Marine Ecosystems: Insights into Saxitoxin and Domoic Acid Genes. Master Marine Biology University of Bremen, defended Oct 2024.

Matz J, Investigation of new and regenerated primary production during summer in Arctic Fjords using ^{13}C and ^{15}N . Carl von Ossietzky Universität Oldenburg, defended May 2024.

Data

Physical oceanography (CTD):

<https://www.pangaea.de/expeditions/bybasis/Heincke>

Cruise Report

HE627: https://dx.doi.org/10.48433/cr_he627

JC228

Seismic structure of fast spreading lithosphere in the Guatemala Basin and the impact of plate bending at deep-sea trenches on the properties of oceanic crust

Authors

GEOMAR Helmholtz Centre for Ocean Research | Kiel, Germany

I. Grevemeyer, Y. Li, I. Klauke, A. Dannowski

University of Southampton & National Oceanography Centre Southampton | Southampton, UK

T. J. Henstock, A. Robinson, A. H. Teagle

Institut de Physics du Globe & Université Paris Cité | Paris, France

M. Marjanovic

Faculty of Geosciences, University Bremen | Bremen, Germany

N. Kaul

The formation, evolution, subduction, and recycling of oceanic lithosphere is a fundamental tenet of plate tectonics. This cycle is the primary mechanism for thermal and chemical exchanges between the solid Earth and the hydrosphere. In collaboration a German-UK consortium conducted an integrated geophysical and geological study during the barter cruise JC228 aboard the British RRS JAMES COOK, sampling fast-spreading ocean lithosphere of the northern Cocos Plate from its formation to subduction in the Mid-America Trench. We collected seismic reflection (MCS) and refraction (WAS) data along a linear transect with grids in three focus areas; two were on the passively cooling oceanic plate, the third spanned the transition into the subduction zone. There, faults that form as the plate bends allow seawater to penetrate through the crust and into the upper mantle and thereby hydrate mantle just before it subducts. Fluid flow associated with these plate bending faults were investigated using geophysical and pore

water data, including high-resolution bathymetry, heat flow and coring. In addition, we surveyed the structure of the oceanic crust drilled at the Site 1256 of the Ocean Drilling Program and International Discovery Program, the first drill hole believed to have sampled the upper part of the gabbroic lower oceanic crust. The cruise JC228 delivered key information on the evolution of oceanic lithosphere and it provides essential site survey information for two IODP Proposals: the flagship MoHole to Mantle initiative (M2M; IODP-805MDP) and the Bend Fault Serpentinization experiment (approved IODP-876Pre).

Drilling a complete section of the oceanic crust is a major challenge and costly. Thus, scientist defined in numerous meetings and workshops criteria any potential MoHole site should satisfy (Ildefonse et al., 2010), defining the best possible site: a) Crust formed at fast-spreading rate (>40 mm yr⁻¹ half rate); b) Simple tectonic setting with very low-relief seafloor and smooth basement relief; away from fracture zones, propagator pseudo-faults, relict overlapping spreading basins, seamounts, or other indicators of late-stage intraplate volcanism. Connection to the host plate active constructive and destructive boundaries would provide important scientific information; c) Crustal seismic velocity structure should not be anomalous relative to current understanding of “normal” fast-spreading Pacific crust, indicative of layered structure; d) A sharp, strong, single-reflection Moho imaged with Multi-Channel Seismic (MCS) techniques; e) A strong wide-angle Moho reflection (PmP), as observed in seismic refraction data, with distinct and clearly identifiable sub-Moho refractions (Pn); f) A clear upper mantle seismic anisotropy; g) A crust formed at an original latitude greater than $\pm 15^\circ$; h) A location with relatively high upper crustal seismic velocities indicative of massive volcanic formations to enable the initiation of a deep drill hole. Satisfying requirements for points a–e is essential for success. More flexibility is allowed in meeting points f–h, which are highly desirable but not essential.

During the GUATOPS/MoHole cruise JC228, we could acquire seismic data of excellent quality, providing clear reflections of the seismic Moho in MCS data. However, the Moho reflector is not always continuous, but still could be observed on all profiles. Instead, wide-angle PmP reflections are observed at all 96 deployed stations and the observation of Pn reveals a strong degree of anisotropy with 7.8 km/s in the slow and 8.4 km/s in the fast direction. Therefore, criteria a) to f) are all full filled, showing an appropriate setting for future deep-drilling. However, criteria c) is fulfilled with respect to the typical layer structure of the oceanic crust, but crust is generally thinner than the global average of 6 km with the thinnest crust being sampled in the west of the study area (~ 4.5 –5 km) and thicker crust in the east (5.5–6 km).

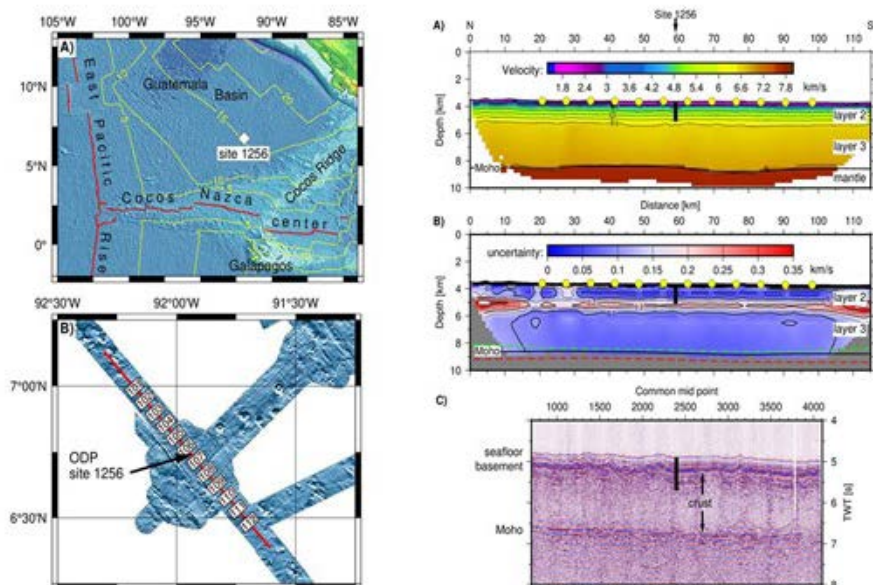


Figure 1: (left) Location map of the seismic refraction and wide-angle survey across Site 1256; (right) Results from the tomographic inversion (A + B) and migration of wide-angle PmP reflections to reveal Moho and mirror imaging to image the sedimentary blanket and basement. Note the this oceanic crust of ~5 km thickness (or 1.5 s two-way travel time); from Grevemeyer et al. (submitted).

In this overview, we will focus on results obtained at ODP Site 1256 and provide a summary of features affecting the structure and properties of the oceanic crust approaching the deep-sea trench where large amount of seawater is believed to infiltrate the oceanic crust and lithosphere (e. g., Grevemeyer et al., 2007; 2018), and provide also constraints on the hydrogeology by studying heat flow anomalies in the trench-outer rise.

Ocean Drilling Program (ODP) Site 1256 was drilled in the Guatemala Basin, eastern Pacific Ocean (Figure 1, left-hand side), sampling superfast spreading crust. It is one of the deepest drill holes sampling intact oceanic crust formed at fast spreading rates and the only site that penetrated gabbroic rocks away from a tectonic window. Two gabbroic sills were sampled at 1157 m and 1283 m below the basement. We collected seismic refraction and wide-angle reflection data across the drill site and the resulting tomography models show that the first encountered gabbro does not mark the top of the seismic boundary between the upper (layer 2) and the lower (layer 3) crust, which we observe 400-500 m deeper. We propose that the drilled gabbroic dikes may represent either shallow intrusions or fluctuations of the magma supply and, hence, varying depth of a migrating magma lens. Seismic tomography and wide-angle migration of mantle reflections (Figure 1, right-hand side) reveal extremely thin crust of 5 ± 0.2 km (i. e., ~1.5 s

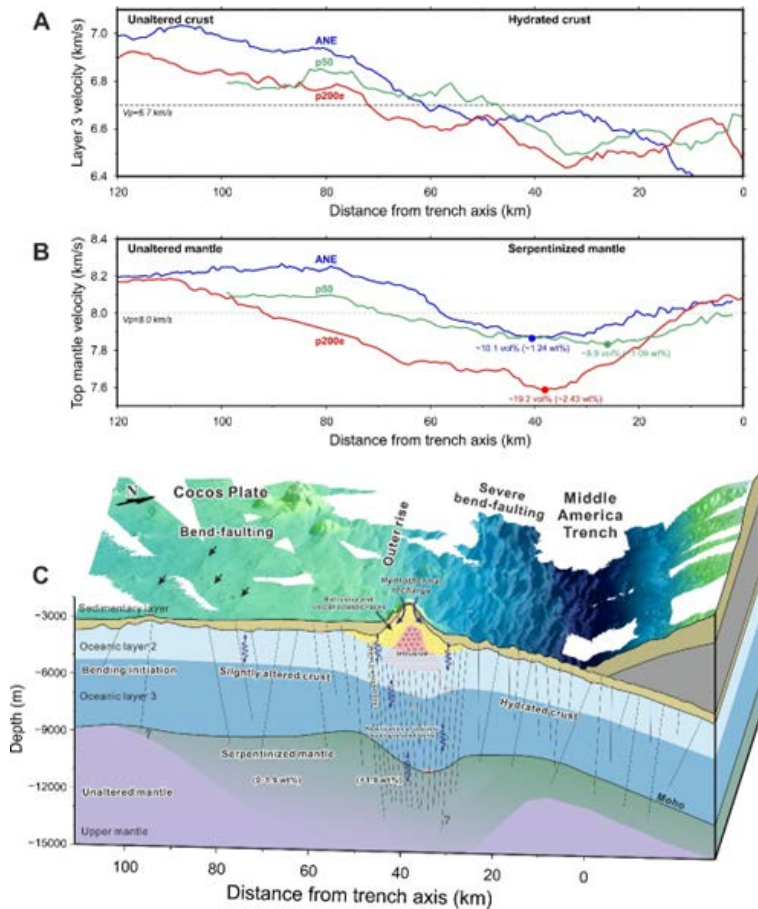


Figure 3: (A) The variation of layer 3 velocity and (B) upper mantle velocity with distance from trench axis. Colored dots mark the maximum serpentinized degree (vol%) and water content (wt%). (C) 3D conceptual model illustrating the role of the seamount at outer rise in entrainment of seawater into the crust and upper mantle. Black arrows mark the onset of bend-faulting observed from bathymetry (from Li et al., 2025).

The subduction of seamounts greatly affects arc volcanism, earthquakes, and tectonic deformation of the overriding plate, but their role during bending and hydration of the incoming plate at subduction zones is poorly understood. The cruise JC228 studied their impact using seismic tomographic results along three profiles (Line P200e acquired during JC228 and two profiles of opportunity from Ivandic et al. (2008) and Miller et al. (2021) and from the Middle America Trench offshore northern Costa Rica. The crustal and upper mantle P-wave velocities decrease towards the trench, with the onset of velocity reduction at ~70 km from the trench axis indicating bend-faulting, alteration, and hydration of the incoming plate. The most prominent low velocity anomaly of 7.6–7.8 km/s in the upper mantle occurs beneath a seamount at the outer rise, indicating enhanced

hydration with 2.4 wt% water content, compared to 1.1–1.3 wt% in the subducting plate away from the seamount. Near the seamount, extremely low heat flow obtained during JC228 (<10 mW/m²) supports vigorous hydrothermal recharge of seawater. Our results (Li et al., 2025) reveal that subducting seamounts efficiently increase the permeability of the oceanic crust prior to subduction, facilitate the migration of seawater into the mantle, exert control on widespread serpentinization and notably promote water recycling back into the Earth's interior.

References

- Grevemeyer I, Ranero CR, Flueh ER, Kläschen D & Bialas J, Passive and active seismological study of bending-related faulting and mantle serpentinization at the Middle America trench, *Earth and Planetary Science Letters* 2007, 258, 528–542, <https://doi.org/10.1016/j.epsl.2007.04.013>.
- Grevemeyer I, Ranero CR & Ivandic M, Structure of oceanic crust and serpentinization at subduction trenches, *Geosphere* 2018, 14, 395–418, <https://doi.org/10.1130/GES01537.1>.
- Grevemeyer I, Henstock TJ, Marjanović M, Papenberg C, Dannowski A, Li Y, Robinson AH & Teagle DAH, Seismic wide-angle constraints on crustal thickness and structure at Ocean Drilling Program Site 1256: how typical are its features for oceanic crust?, *Geology*, in review.
- Ildefonse B, et al., The MoHole: A Crustal Journey and Mantle Quest, Workshop in Kanazawa, Japan, 3–5 June 2010. *Scientific Drilling* 2010, 10, 56–62, <https://usoceandiscovery.org/past-workshops-old/the-mohole-a-crustal-journey-and-mantle-quest>.
- Ivandic M, Grevemeyer I, Berhorst A, Flueh ER & McIntosh K, Impact of bending related faulting on the seismic properties of the incoming oceanic plate offshore of Nicaragua: *Journal of Geophysical Research, Solid Earth* 2008, 113, <https://doi.org/10.1029/2007JB005291>.
- Li Y, Grevemeyer I, Robinson AH, Henstock TJ, Marjanović M, Dannowski A, Kaul K, Klaucke I, Vannucchi P, Hilbert H-S, Teagle DAH & Morgan JP, Impact of seamounts on the hydration of subducting plates, *Geology*, 2025, <https://doi.org/10.1130/G53355.1>.
- Miller NC, Lizarralde D, Collins JA, Holbrook WS & van Avendonk HJA, Limited Mantle Hydration by Bending Faults at the Middle America Trench: *Journal of Geophysical Research, Solid Earth* 2021, 126, e2020JB020982, <https://doi.org/10.1029/2020JB020982>.

Scientific Output

List of Publications

Grevemeyer I, Henstock TJ, Marjanović M, Papenberg C, Dannowski A, Li Y, Robinson AH & Teagle DAH, Seismic wide-angle constraints on crustal thickness and structure at Ocean Drilling Program Site 1256: how typical are its features for oceanic crust?, *Geology*, in review.

Li Y, Grevemeyer I, Robinson AH, Henstock TJ, Marjanović M, Dannowski A, Kaul K, Klaucke I, Vannucchi P, Hilbert H-S, Teagle DAH & Morgan JP, Impact of seamounts on the hydration of subducting plates, *Geology* 2025; <https://doi.org/10.1130/G53355.1>.

List of conference presentations

2023 | **Oceanic crustal structure at ODP Site 1256 from seismic wide-angle tomography and down-hole logging**, Annual Meeting of the European Geoscience Union, Vienna, Austria.

2023 | **Multichannel Seismic Imaging of Oceanic Lithosphere in the Guatemala Basin – Observations from a Site Survey for Potential MoHole Drilling**, Fall Meeting of the American Geophysical Union, San Francisco, U.S.A.

2023 | **Site survey for potential MoHole drilling sites in the Guatemala Basin**, Annual Meeting of the European Geoscience Union, Vienna, Austria.

2023 | **Site survey for potential MoHole drilling sites in the Guatemala Basin**, IODP National Annual Meeting, France.

2023 | **Wide-angle seismic imaging of crust and upper mantle structure for a potential Mohole drilling site – the Guatemala Basin**, IODP Annual meeting, UK.

2023 | **Oceanic Crustal Structure of the Guatemala Basin: Pre-site Survey for IODP Flagship Project “MoHole”**, Fall Meeting of the American Geophysical Union, San Francisco, U.S.A.

2023 | **Wide-Angle Seismic Imaging of Crust and Upper Mantle Structure Along a Ridge Flow-Line in the Guatemala Basin – Observations from a Site-Survey for Potential MoHole Drilling**, Fall Meeting of the American Geophysical Union, San Francisco, U.S.A.

2024 | **Bending-related faulting, hydration, and mantle serpentinization in the incoming Cocos Plate at Middle America Trench: Evidence from wide-angle seismic refraction data**, Annual Meeting of the European Geoscience Union, Vienna, Austria.

Data

Seismic wide-angle/OBS data P100:
<https://doi.org/10.1594/PANGAEA.974489>

Seismic wide-angle/OBS data P400:
<https://doi.org/10.1594/PANGAEA.974808>

Seismic wide-angle/OBS data P200:
<https://doi.org/10.1594/PANGAEA.974799>

Seismic wide-angle/OBS data P200w:
<https://doi.org/10.1594/PANGAEA.977816>

Seismic wide-angle/OBS data P200e:
<https://doi.org/10.1594/PANGAEA.977815>

Magnetics, gravity and sub-bottom profiler data:
<https://dx.doi.org/10.5285/3b26ac37-0cd6-6d2c-e063-7086abc0273f>

Multi-channel seismic data:
<https://dx.doi.org/10.5285/3affff1b-164d-5d76-e063-7086abc06977>

Raw geophysical data, navigation and logs from RRS James Cook expedition JC228:
<https://dx.doi.org/10.5285/3b4d4347-d2ec-2a6a-e063-7086abc0145d>

Processed multi-beam bathymetry grid from RRS James Cook expedition JC228:
<https://dx.doi.org/10.5285/3b23c40a-45e7-193f-e063-7086abc055dd>

Cruise Report

JC228:
https://www.bodc.ac.uk/resources/inventories/cruise_inventory/reports/jc228.pdf

MSM105

Effects of Variability in Physical Forcing on Carbon and Oxygen Budgets in the Northern Benguela Upwelling System

Authors

Leibniz-Institute for Baltic Sea Research Warnemünde (IOW) | Rostock, Germany

V. Mohrholz, K. Amorim, S. Beier, Ph. Braun, Ch. Burmeister, G. Dangl, J. Fabian, M. Glockzin, M. Gogina, T. Heene, K. Jürgens, M. Kolbe, M. Kossack, Ch. Meeske, F. Pohl, S. Porrmann, G. Rehder, B. Sabbaghzadeh, M. Schmidt, H. Schulz-Vogt, A. Witzleb, M.L. Zettler

Center for Marine Environmental Sciences (MARUM) – Bremen University | Bremen, Germany

M. Kossack, S. Porrmann, A. Witzleb

The expedition MSM105 was part of the field campaigns of the EVAR project “The Benguela Upwelling System under climate change – Effects of variability in physical forcing on carbon and oxygen budgets”, funded by the BMBF. The cruise was the second EVAR field campaign. It combined high resolution in-situ measurements of water properties, nutrient and trace gas concentrations with on board incubation experiments and an intensive sampling program of key parameters of the ecosystem. The expedition was carried out in austral summer when the oxygen deficit in the OMZ on the Namibian shelf increases towards its maximum extent in late March to April. The cruise delivered the complementary data to the first EVAR field campaign in August/September 2019. The major goal of this second EVAR expedition was to obtain high-resolution data on the variability of present-day physical forcing of the Benguela Upwelling System (BUS). The present and past variability of oxygen supply as well as their key biogeochemical feedbacks as documented in sediment archives has been analyzed. The response of microbially driven processes to variations in the redox scheme over the ranges observed today and in the geological past was investigated in targeted experiments to understand their impact on oxygen, carbon and nutrient budgets and their influence on the production of greenhouse gases. Linking variability of physical and biogeochemical forcing with ecosystem response will help to develop possible trajectories of future upwelling systems in a changing climate.

Hydrography and Mixing

The cruise met a situation after a longer period of coastal upwelling off central Namibia. A band of cold water stretching along the Namibian coast throughout the northern BUS. The hydrographic conditions on the shelf were characterised by weak coastal upwelling. In the north at 18°S, warm and saline tropical water dominated. The high surface temperature created a salinity maximum at the surface, while oxygen was generally depleted below this layer, with minimum concentrations below 40 $\mu\text{mol kg}^{-1}$ occurring between 200 and 400 m depth. In the center of the NBUS at 23°S, salinity and temperature patterns indicate coastal upwelling, reaching depths of about 150 m. This brought colder subsurface water to the surface. Near the coast, only a thin layer of warm surface water was present, with a westward-deepening mixed layer. The colder, less saline upwelled water was rapidly heated and stabilized, overlying more saline water as it moved offshore with Ekman transport. Oxygen was depleted below 200 m and nearly exhausted across the broad shelf, with a few stations showing sulfidic waters near the coast. At 25°S, salinity variability on the shelf was lower than at 23°S, and the layer of less saline surface water was displaced far offshore. Oxygen was almost entirely depleted on the shelf, with a thick anoxic bottom layer exhibiting partially sulfidic conditions. Near the coast, this anoxic layer extended almost to the surface. Turbulent mixing was confined to the shelf edge and some areas on the inner shelf (Figure 1).

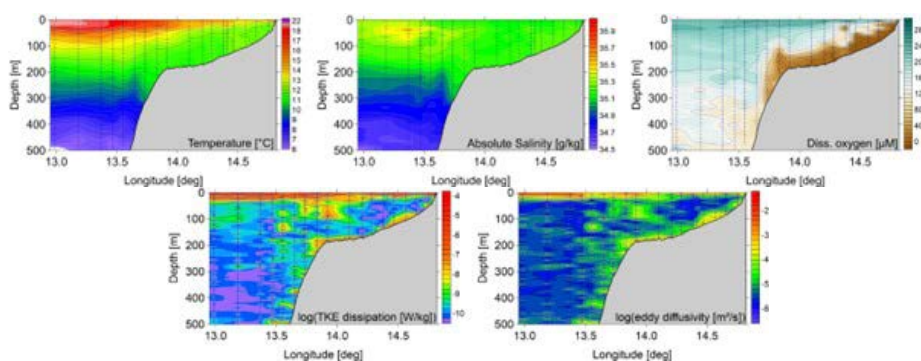


Figure 1: Hydrographic conditions on the zonal transect at 25°S (Black rock). Temperature, salinity and dissolved oxygen in the upper 500m (upper panels, left to right). Dissipation rate of turbulent kinetic energy (lower panel left) and eddy viscosity (lower panel right) gathered with the MSS microstructure profiler between 27th and 31st January 2022.

Trace Gas Dynamics

The high surface productivity triggered by nutrient-rich Benguela upwelled waters results in significant enrichment of organic carbon in the sub-surface waters due to enhanced mineralization in the water column and benthic fluxes. Hence, microbial

O₂-consuming processes are promoted, driving oxygen depletion that favors trace gases i. e. methane (CH₄) and nitrous oxide (N₂O) production at relatively shallow depths. During upwelling events, gas-rich subsurface waters are also transported towards the surface waters, enhancing trace gas sea-air. The variability of these fluxes on seasonal and shorter timescales was investigated to understand the intensity of the Benguela upwelling system as source of these greenhouse gases relative to the atmosphere. The data might serve as a base for projections under a changing climate.

Nutrients and Microbial Ecology

The high temporal variability of the system was investigated using high-resolution nutrient profiles from a pumped CTD system. On the central shelf above the mud belt, the water column was sampled three times over three weeks.

On 26 January 2022, oxygen and sulfide did not overlap; nitrate disappeared at the upper sulfidic horizon, with a pronounced nitrite peak between oxygenated and sulfidic waters, indicating active anaerobic sulfide oxidation. By 30 January, oxygenated and sulfidic layers were closer, nitrate extended slightly further into the sulfidic zone, and the nitrite peak was less pronounced, suggesting more sulfide oxidation by oxygen.

7 February, oceanographic conditions had changed markedly. Oxygen was restricted to the upper layer, while nitrate was present throughout the water column. The bottom water originated from a different source, indicated by lower ammonia and phosphate levels. High nitrite concentrations occurred throughout the column, peaking at 35 m (19 µM) at a small oxygen intrusion, implying nearly complete nitrate reduction. Further analysis is needed to explain this extreme nutrient and gas variability.

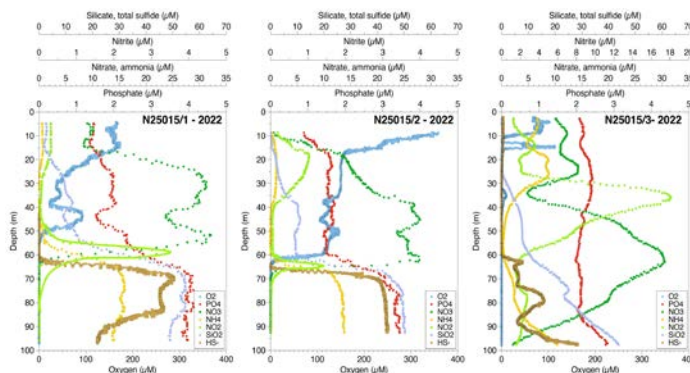


Figure 2: PumpCTD profiles of nutrients, oxygen and total sulfide measured at the 26.01., 30.01., and 7.02. 2022 at station N25015. Note the changed scale of the nitrite axis in the third profile.

The regularly occurring oxygen-deficient zones of the BUS are sites of important biogeochemical transformations within several element cycles, mediated by different groups of prokaryotes. When nitrate containing water intersects or mixes with sulfidic water, denitrification can be coupled to sulfide oxidation. As an intermediary or side product of denitrification and nitrification N_2O (nitrous oxide) is formed, making marine oxygen minimum zones (OMZs) to a significant source of this climate relevant trace gas. The distribution and spatio-temporal variability of these processes, as well as the microbial response towards fluctuating conditions was also addressed during the cruise.

Benthic Ecology and Biodiversity

The main aim of benthic fauna sampling was to (1) compare macrobenthic diversity in the core and edges of the Oxygen Minimum Zone (OMZ) and (2) identify strategies allowing survival in this harsh environment, focusing on behaviour, metabolism, morphology, and symbionts.

In the first focus area, the study examined macrozoobenthos types, distribution, and environmental requirements in terms of sediment, depth, and oxygen. Covering 17°S to 25°S and 25–1523 m depth, a total of 534 taxa were recorded, making this the most comprehensive survey of Namibian OMZ macrofauna to date. Hierarchical clustering based on abundance and biomass revealed slightly different assemblages. More than 10 new species were described, and the 2025 book on Namibian marine bivalves provides the first identification guide, review, and zoogeographical overview for the region.

The second focus area investigated adaptation mechanisms of selected benthic species. Transcriptomic and metabolomic responses of the bivalve *Lucinoma capensis* were studied under normoxia, hypoxia, and recovery, focusing on gills and digestive gland. The gills showed strong transcriptional responses to oxygen fluctuations, whereas the digestive gland remained more stable.

Sediment Geochemistry

The geochemical work focused on collecting pore-water and sediment samples from the diatomaceous mud belt off Namibia, as well as suspended particulate matter (SPM) from the water column. Undisturbed surface sediments were recovered using a multicorer (MUC). Enrichments of molybdenum (Mo) and uranium (U) serve as indicators of redox conditions in oxygen-depleted marine palaeoenvironments. Seasonal fluctuations between oxygenated and anoxic sulfidic bottom waters, along with lateral sediment transport, can alter the primary Mo and U signals in the sediment. We investigated how spatially and seasonally

variable redox conditions influence authigenic Mo and U enrichments in organic-rich (TOC) mud-belt sediments. A mass balance for each element was used to analyse the mechanisms of supply, accumulation, and recycling. Mo is transported in dissolved form across the sediment–water interface, with maximum fluxes during the austral summer under anoxic, strongly sulfidic conditions. Observed benthic Mo fluxes of up to 37 nmol cm⁻² yr⁻¹ are the highest recorded in sulfidic surface sediments and match solid-phase accumulation rates. Diffusive U fluxes are generally too low to account for sedimentary enrichment, indicating that U is mainly supplied in particulate form. In anoxic areas, shallow maxima of dissolved U just below the sediment–water interface and low sedimentary U suggest recycling back to the bottom water. Where bottom-water oxygen varies seasonally, the depth of Mo and U removal from pore water shifts within the sediment, defining a ~20 cm layer where both elements accumulate in the solid phase.

Scientific Output

List of Publications

Zettler ML & Hoffman L, *Nucula* (Nuculidae, Bivalvia) from upper bathyal depths off Namibia, *Iberus* 2022, 40(2), 291–299, <https://doi.org/10.5281/zenodo.6902206>.

Amorim K & Zettler ML, Gradients and instability: Macrozoobenthic communities in the Benguela Upwelling System off Namibia, *Estuar. Coast. Shelf Sci.* 2023, 291, 108421, doi: 10.1016/j.ecss.2023.108421.

Kossack M, Scholz F, Anderson CH, Vosteen P, Su CC, Mohrholz V & Zabel M, Sedimentary molybdenum and uranium cycling under seasonally contrasting redox conditions on the Namibian Shelf, *Geochim. Cosmochim. Acta* 2023, 358, 174–191, doi: 10.1016/j.gca.2023.08.014.

Zettler ML & Hoffman L, *Condylocardiidae* (Bivalvia) from Namibia, *Basteria* 2023, 87, 2–10 <https://basteria.nl/wp-content/uploads/2025/05/Basteria-87-1-Zettler-Hoffman-Condylocardiidae.pdf>.

Zettler ML, Bastrop R & Lowry JK, Ten thousand kilometres away and still the same species? The mystery of identity of *Scopelocheirus* sp. (Amphipoda: Scopelocheiridae) from the South Atlantic, In: Berents PB, Ah Yong ST, Myers AA, Fanini L (eds), *Festschrift in Honour of James K. Lowry*, *Records of the Australian Museum* 2023, 75, 609–622, <https://doi.org/10.3853/j.2201-4349.75.2023.1896>.

Bick A & Zettler ML, Description of three new species of Amphitritides Augener, 1922 (Terebellida, Annelida) from the coast of Namibia (South West Africa), Zootaxa 2024, 5446 (1), 42–64 <https://doi.org/10.11646/zootaxa.5446.1.2>.

Hoffman L, Wienberg C, Lisher M & Zettler ML, Occurrence of Adacnarca (Bivalvia: Philobryidae) of Late Pleistocene age from the continental shelf off Namibia and notes on species from South Africa, Basteria 2024, 88(2), 264–270, <https://basteria.nl/wp-content/uploads/2025/05/Basteria-88-2-Hoffman-et-al-Adacnarca-Namibia.pdf>.

Hoffman L & Zettler ML, Galeommatoidea (Bivalvia) from Namibia (Part 2), Iberus 2024, 42(2), 155–164, <https://doi.org/10.5281/zenodo.13730694>.

Hoffman L & Zettler ML, Neoleptonidae (Bivalvia) from Namibia, Iberus 2024, 42(2), 165–173 <https://doi.org/10.5281/zenodo.13730736>.

Dangl G, Frey C, Hassenrück C, Sabbaghzadeh B, Wäge-Recchioni J, Lehmann MF, Schulz-Vogt H, Fabian J, Ley M, Rehder G & Jürgens K, Processes and microorganisms driving nitrous oxide production in the Benguela Upwelling System, Limnol. Oceanogr. 2025, 70, 850–869, doi: 10.1002/lno.12811.

Sokolova IM, Sokolov EP, Piontkivska H, Timm S, Amorim K & Zettler ML, Symbiosis beyond nutrition: Transcriptomic and metabolic responses to hypoxia in the holobiont Lucinoma capensis from an Oxygen Minimum Zone, Molecular Ecology 2025 (under Review).

Zettler ML & Hoffman L, Marine Bivalves of Namibia, Harxheim: ConchBooks 2025, 358 S., <https://www.conchbooks.de/?t=53&u=68307>.

List of conference presentations

2022 | **The Relation of Wind-Driven Coastal and Offshore Upwelling in the Benguela Upwelling System** Open Science Conference on Eastern Boundary Upwelling Systems (EBUS): Past, Present and Future & Second International Conference on the Humboldt Current System, Lima, Peru

2023 | **Low confidence in multi-decadal trends of wind-driven upwelling across the Benguela upwelling system due to internal climate variability** TAV-PIRATA/TRIATLAS MEETING, Banyuls sur mer, France

Data

Master track of MSM105:

<https://doi.org/10.1594/PANGAEA.947401>

Sediment echosounder processed data:

<https://doi.org/10.1594/PANGAEA.973170>

Multibeam bathymetry raw data:

<https://doi.org/10.1594/PANGAEA.965106>

Trace gases air daily means:

<https://doi.org/10.1594/PANGAEA.959647>

Trace gases CH₄, N₂O, and CO₂ discrete water samples:

<https://doi.org/10.1594/PANGAEA.959667>

Sea surface trace gases:

<https://doi.org/10.1594/PANGAEA.959660>

Physical oceanography data:

<https://doi.org/10.1594/PANGAEA.956306>

ADCP current measurements:

<https://doi.org/10.1594/PANGAEA.946310>

Sediment echosounder raw data:

<https://doi.org/10.1594/PANGAEA.973122>

Sequential iron extraction, pore water and solid phase analyses for sediment cores:

<https://doi.org/10.1594/PANGAEA.972991>

Biogeochemical particle fluxes:

<https://doi.org/10.1594/PANGAEA.968901>

Cruise Report

MSM105: https://doi.org/10.48433/cr_msm105

MSM107

Unravelling Lateral Transport, Organic Matter Transformation, and Seafloor Dynamics on the Irish Continental Margin: Key Results from MSM107

Authors

Alfred Wegener Institute for Polar and Marine Research | Bremerhaven, Germany

M. Iversen, O. Karakus, C. Konrad, A. Kraberg, S. Murawski, B. Wei

MARUM, Centre for Marine Environmental Sciences at the University of Bremen | Bremen, Germany

R. Bernhard, L. Hufnagel, M. Iversen, N. Kniebel, A. Lefebvre, H. Marchant, E. Miramontes-Garcia, A. Mundanatt, N. Nguyen, L. Stock, K. Zonneveld

University of Bremen, Department for Geosciences | Bremen, Germany

R. Bernhard, M. Iversen, B. Kockisck, A. Lefebvre, E. Miramontes-Garcia, T. Schwenk

Max Planck Institute for Marine Microbiology | Bremen, Germany

H. Marchant, A. Mundanatt, N. Nguyen, L. Stock, J. Stührenberg

Extended Abstract

The expedition **MSM107** on board *RV Maria S. Merian* targeted the complex interplay between physical transport processes, dissolved and particulate organic matter dynamics, and seafloor ecosystem functioning along the Irish shelf and slope. Recent analyses emerging from the expedition provide new perspectives on how continental margins shape the transformation and sequestration of organic matter. Together, they highlight the Irish margin as a hotspot of **rapid offshore export, episodic downslope flushing**, and **biogeochemical reactivity** in both dissolved and particulate pools (Blight et al. 2024, Wang et al. 2025, Wei et al. 2024).

Background and Scientific Motivation

Continental margins represent dynamic transition zones where physical forcing, sediment redistribution, and complex biogeochemical processes intersect. Despite their relatively small surface area, margins contribute disproportionately to global carbon sequestration and benthic biodiversity. MSM107 focused on a segment of the Irish shelf and upper slope, a region characterized by strong topographic gradients, bottom-intensified currents, and a mosaic of geomorphological structures such as sediment drifts, canyons, and contourite channels.

The overarching scientific goals of MSM107 were to:

1. Quantify lateral and vertical transport pathways of dissolved and particulate organic matter (DOM and POM).
2. Assess the molecular composition, bioavailability, and alteration of exported organic matter.
3. Characterize sedimentological and hydroacoustic indicators of episodic downslope transport.
4. Provide a holistic framework for understanding organic matter fate in a margin system undergoing increasing pressure from climate variability and human activity.

Physical Forcing and Sediment Dynamics

Results from multibeam and sediment-core analyses demonstrate that the Irish margin is shaped by recurrent high-energy events, likely linked to storms, dense-water cascades, and reactivation of slope sediments. Hydroacoustic data from MSM107 revealed distinct erosional features, sediment waves, and mass-transport deposits, collectively indicating episodic downslope flushing (Wang et al. 2025).

These processes appear to act as major controls on the distribution of both fine and coarse fractions, affecting seabed habitats and influencing the ultimate fate of carbon transported from the shelf. The mapping and interpretation of these features underscore the sensitivity of continental margins to intermittent forcing events that can mobilize large amounts of previously stored material.

Down-Slope Transport of Fresh DOM

The study by Wei et al. (2024) presents the first direct evidence of rapid downslope transport of fresh dissolved organic matter to depths exceeding 3000 m. Using radiocarbon signatures, FT-ICR-MS molecular fingerprints, and conservative tracer analysis, Wei et al. (2024) demonstrate that newly formed surface-derived DOM can bypass remineralization in the upper ocean and reach the deep sea within time scales of weeks to months.

This challenges the prevailing view that deep-ocean DOM is largely composed of highly aged, refractory material. Instead, MSM107 data show that fast physical pathways, possibly connected to bottom-intensified currents and slope flushing events, directly inject fresh DOM into the deep Irish margin, where it may contribute to long-term sequestration.

Molecular Composition and Reactivity of Exported DOM

Bligh et al. (2024) provide new insights into the molecular composition of dissolved organic matter (DOM) exported from the Irish shelf system. Using high-resolution mass spectrometry and targeted glycomics, they identify a distinct class of fucose-rich oligosaccharides (FOS) that are exported from surface waters and unexpectedly persist into the mesopelagic and deep ocean. Although these carbohydrates are structurally similar to compounds typically considered labile, Bligh et al. (2024) show that FOS escape rapid microbial degradation. The analyses from MSM107 reveal chemical features, including partial sulfation and glycan motifs, that likely protect these compounds from enzymatic deconstruction, helping explain their survival during long-range transport.

These results challenge the prevailing view that deep-ocean DOM is composed exclusively of highly processed, refractory molecules, and instead demonstrate that even “labile-like” carbohydrates can be selectively preserved in the ocean interior. The findings in Bligh et al. (2024) therefore complements the physical and biogeochemical findings from MSM107 by identifying a molecular mechanism that contributes to the persistence of specific carbohydrate-rich DOM components transported from continental margins.

Particle Dynamics and Seafloor Mapping

Hydroacoustic observations obtained during MSM107 revealed dense near-bed particle layers and intermittent turbidity signals. These layers correspond to resuspension events and bottom-nepheloid layers, which may serve as efficient vectors for POM export beyond the shelf break.

Sedimentological work during MSM107 identifies a series of sediment drifts and mass-transport features that mirror the spatial pattern of these nepheloid layers. This combined interpretation provides a structural and process-based link between modern particle dynamics and long-term sediment deposition.

The alignment of drift morphology with bottom-current pathways suggests a persistent role of contourite transport in shaping margin stratigraphy.

In Situ Optical Observations of Particles, Zooplankton, and Vertical Transport Processes

Complementary to the geochemical and hydrodynamic analyses, MSM107 has advanced a comprehensive observational framework using in situ imaging systems. These optical platforms, including high-resolution profiling cameras, in situ size-specific settling velocities, detailed information of particle sizes and types at high spatial and temporal resolution allow continuous quantification of particles ranging from single phytoplankton cells and aggregates to marine snow, zooplankton, gelatinous organisms, and micronekton. By resolving particle abundance, size spectra, and sinking velocities in situ, we can directly link biological community structure to vertical and lateral transport dynamics. Time-resolved imaging combined with hydroacoustics further enables quantification of diel vertical migration (DVM) of zooplankton and micronekton, capturing their role in actively transporting carbon between the surface and deeper layers. These measurements reveal how the interplay between gravitational settling, biologically mediated transport, and lateral advection shapes the fate of organic matter exported from shelves and fronts. When combined with detailed analyses of the composition and current measurements, the optical data provide a mechanistic description of carbon export efficiency, attenuation through the mesopelagic zone, and the potential for long-term sequestration. This integrated approach demonstrates that biological behavior, particularly zooplankton migration patterns and aggregate formation, can exert control on the magnitude and direction of carbon fluxes that is comparable to physical forcing and geochemical reactivity.

Benthic Nitrogen Cycling and Seafloor Biogeochemical Processing

In addition to the pelagic and lateral transport processes, MSM107 included dedicated benthic investigations to quantify how the seafloor modulates nutrient regeneration and carbon-nitrogen coupling. Sediment cores and grabs were used to collect sediments that were subsequently incubated in order to characterize nitrification, denitrification, and anammox across the Irish slope and basin. These measurements show that benthic nitrogen transformations are tightly

linked to organic matter supply from both vertical settling and downslope lateral transport. We are currently linking the pelagic and benthic studies to understand how microbial and zooplankton turnover processes regulate nutrient availability, stoichiometry of exported material, and influencing the long-term sequestration potential of organic carbon. When integrated with particle flux and DOM analyses, the benthic data reveal a coupled pelagic–benthic system in which physical transport, biological activity, and microbial processes jointly determine the fate of carbon and nitrogen exported from continental margins.

Synthesis and Emerging Conceptual Framework

Together, these studies illustrate a highly coupled and dynamic system on the Irish continental margin, in which physical, biological, and microbial processes jointly regulate carbon and nutrient fluxes:

- **High-energy physical events** such as storms, dense-water cascades, and slope reactivation mobilize sediments and particle-bound organic matter, driving episodic downslope flushing and shaping the distribution of particulate and dissolved material.
- **Bottom-intensified flows and geomorphological pathways** facilitate rapid transport of both DOM and POM from shelf to deeper basins, while preserving specific molecular components such as fucose-rich oligosaccharides.
- **Biological processes**, including diel vertical migration of zooplankton and micronekton and aggregate formation, actively redistribute organic carbon vertically and laterally, modulating the magnitude and timing of carbon export and attenuation in the mesopelagic.
- **Benthic transformations** of nitrogen and organic matter influence nutrient regeneration and stoichiometry, linking the supply of settling material to microbial and faunal processing at the seafloor and thereby affecting long-term carbon sequestration.
- **Integrated perspectives** from in situ imaging, hydroacoustics, sedimentology, and molecular analyses reveal that the Irish margin functions not merely as a conduit, but as a **process-enhancing system**, where interactions among physics, biology, and chemistry optimize carbon export efficiency, modulate remineralization, and contribute to long-term sequestration.

This comprehensive framework emphasizes that carbon and nutrient fluxes along continental margins cannot be understood from physical transport or biogeochemistry alone; instead, they emerge from the **synergistic interaction of**

physical forcing, particle dynamics, biological activity, and benthic processing, providing new mechanistic insights into how margins shape the fate of organic matter in the deep ocean.

References

Wang L, Lefebvre A, Schwenk T, Kockisch B, Wheeler A, Iversen M & Miramontes E, Contourite distribution on the continental slope off NW Ireland, Rockall Through (NE Atlantic Ocean): genesis and evolution, *Geomorphology* 2025, 482, 109788, doi: 10.1016/j.geomorph.2025.109788.

Wei B, Seidel M, Mollenhauer G, Lefebvre A, Miramontes E, Grotheer H, Elvert M, Wendt J, Dittmar T & Holtappels M, Rapid Down-Slope Transport of Fresh Dissolved Organic Matter to the Deep Ocean in the Eastern North Atlantic, *Geophysical Research Letters* 2024, 51(21), e2024GL110349, doi: 10.1029/2024GL110349.

Blight M, Buck-Wiese H, Sichert A, Bercovici S K, Hellige I, Marchant H, Iversen M, Sauer U, Dittmar T, Arnosti C, Liebeke M & Hehemann J-H, Selective preservation of fucose-rich oligosaccharides in the North Atlantic Ocean, *Science of the Total Environment* in review, archived at bioRxiv, doi: 10.1101/2024.09.20.613644.

Scientific Output

List of Publications

Wang L, Lefebvre A, Schwenk T, Kockisch B, Wheeler A, Iversen M & Miramontes E, Contourite distribution on the continental slope off NW Ireland, Rockall Through (NE Atlantic Ocean): genesis and evolution, *Geomorphology* 2025, 482, 109788, doi: 10.1016/j.geomorph.2025.109788.

Wei B, Seidel M, Mollenhauer G, Lefebvre A, Miramontes E, Grotheer H, Elvert M, Wendt J, Dittmar T & Holtappels M, Rapid Down-Slope Transport of Fresh Dissolved Organic Matter to the Deep Ocean in the Eastern North Atlantic, *Geophysical Research Letters* 2024, 51(21), e2024GL110349, doi: 10.1029/2024GL110349.

Blight M, Buck-Wiese H, Sichert A, Bercovici S K, Hellige I, Marchant H, Iversen M, Sauer U, Dittmar T, Arnosti C, Liebeke M & Hehemann J-H, Selective preservation of fucose-rich oligosaccharides in the North Atlantic Ocean, Science of the Total Environment in review, archived at bioRxiv, doi: 10.1101/2024.09.20.613644.

List of conference presentations

2025 | **The Living Carbon Pump: From Microbial Aggregates to Global Carbon Sequestration** Invited talk at Institut Méditerranéen d'Océanologie, Marseille, France.

2025 | **Is the biological carbon pump really in steady state?** Invited talk at Laboratoire d'Océanographie de Villefranche, Villefranche, France.

2025 | **Comparing POM Fluxes from Free-Drifting Sediment Traps across the Atlantic Ocean** The Ocean Floor Symposium, Bremen, Germany.

2025 | **Quantifying the distribution of nepheloid layers off NW Ireland, Rockall Through (NE Atlantic Ocean): response to hydrodynamics** The Ocean Floor Symposium, Bremen, Germany.

2024 | **Rapid lateral transport of fresh dissolved organic matter to the deep ocean** EGU General Assembly 2024, Vienna, Austria.

Data

Navigation / ship track (1 second resolution):
<https://doi.org/10.1594/PANGAEA.948098>

Continuous thermosalinograph (TSG) along MSM107 track:
<https://doi.org/10.1594/PANGAEA.958268>

Physical oceanography (CTD, T, S, O₂, turbidity, etc.):
<https://doi.org/10.1594/PANGAEA.967679>

Lowered ADCP (LADCP) current profiles:
<https://doi.org/10.1594/PANGAEA.972530>

Multibeam water column raw data (Kongsberg EM 122):
<https://doi.org/10.1594/PANGAEA.965130>

Multibeam water column raw data (Kongsberg EM 712):
<https://doi.org/10.1594/PANGAEA.965748>

Multibeam bathymetry raw data (EM 122):
<https://doi.org/10.1594/PANGAEA.965122>

Isotope composition of DOM (surface & bottom):
<https://doi.org/10.1594/PANGAEA.969095>

Molecular composition (FT-ICR-MS) of SPE-DOM (surface & bottom):
<https://doi.org/10.1594/PANGAEA.969105>

Cruise Report

MSM107: https://doi.org/10.48433/cr_msm107

MSM109

Discovery of the first hydrothermal field along the 500-km-long Knipovich Ridge – Results from R/V MARIA S. MERIAN cruise MSM109

Authors

MARUM – Center for Marine Environmental sciences, University of Bremen | Bremen, Germany

T. Kleint, G. Bohrmann, K. Streuff, M. Römer, D. Smrzka, A. Röhler, T. Pape, Ch. Kleint, Ch. Hansen, Ch. dos Santos Ferreira, M. Walter, G. Macedo de Paula Santos, W. Bach

Norwegian Offshore Directorate (NOD) | Stavanger, Norway

S.-M. Knutsen, N.-R. Sandstå

Although ultraslow spreading ridges represent a quarter of all spreading ridges globally, very little is known about their hydrothermal systems. The Jøtul hydrothermal field is the first to be discovered along the 500-km-long ultraslow-spreading Knipovich Ridge and is significant, because it represents a new link between the active hydrothermal systems of Loki's Castle at the bend of Mohs and Knipovich Ridges and the Aurora hydrothermal field of the Gakkel Ridge (German et al. 2022). Since these systems are separated by a distance of more than 1000 km, the discovery of the Jøtul hydrothermal field is important for the understanding of chemosynthetic faunal community distribution. Furthermore, unlike in other hydrothermal fields at ultraslow spreading ridges, where volcanic activity is particularly linked to AVR, (e. g. Lokis's Castle; Pedersen et al. 2010), the Jøtul hydrothermal field is actually located ~5 km west of the Brøgger AVR. This location at the eastern boundary fault of the Knipovich rift valley coincides with the slope aprons of the Svalbard continental margin. One reason for the peripheral location of the Joetul field in the Knipovich rift graben is possibly the special tectonic structure of the ridge with its oblique spreading character and the non-transform discontinuity, which is indicated in the bathymetry of the seafloor south of the hydrothermal field (Figure 1).

During research expedition MSM109 ROV QUEST discovered hydrothermal activity, after anomalies had been detected in the water column. Using a CTD with Niskin water samplers, the near-bottom sea water parameters were investigated along four 2.7–4 km long, N-S and E-W trending towed, yo-yoing (tow-yo) profiles in a see-saw pattern between 2,500 and 3,200 m water depth. In addition to the usual sensors, an ORP (oxidation-reduction potential) sensor detected changes in the Eh value (ΔEh) indicative of hydrothermal input (Figure 2). Combined with samples from stationary CTD casts, the tow-yo samples were used to determine the concentrations of dissolved methane close to the Jøtul field area in water depths between 2,100 and 3,000 m. Dissolved methane concentrations around 10 nmol/L and less likely represent background values, whereas values around 100 or 1,000 nmol/L are related to emissions from strong seafloor sources. Some measurements showed values exceeding 3,000 nmol/L, with a maximum of 4,991 nmol/L.

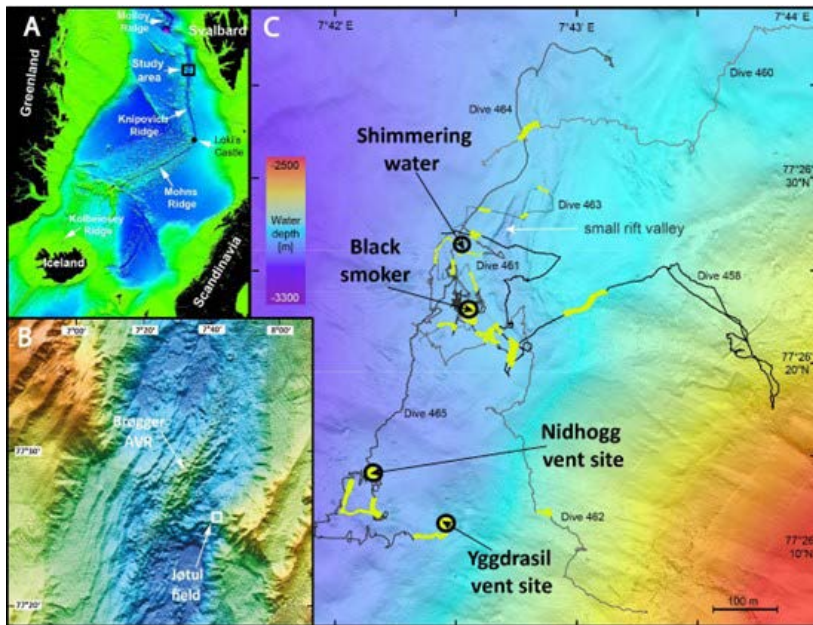


Figure 1: **A**, Map of the Norwegian-Greenland Sea (GEBCO data) with locations of active seafloor spreading centers and the study area. **B**, Detailed map of the study area (ship-based multibeam data acquired during cruise MSM109) including the Brøgger Axial Volcanic Ridge (AVR) and the newly discovered hydrothermal active area called Jøtul hydrothermal field. **C**, AUV-based bathymetry of the Jøtul hydrothermal field (data acquired during cruise MSM109 and provided by NOD). Track lines of ROV dives are shown and track portions, where hydrothermal activity was visually observed, are marked in yellow. Four sites were sampled for fluids during MSM109 and are indicated by circles (from Bohrmann et al. 2023).

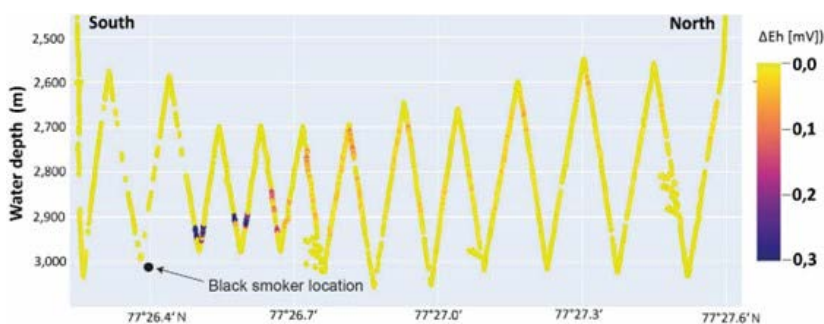


Figure 2: South-North plot of oxidation-reduction potential against water depth over Jøtul hydrothermal field. Data were recorded in mV (ORP sensor) along tow-yo CTD-15, which shows an example of the water column survey. The distribution of higher Eh values show how the hydrothermal plume water is rising upwards and drifting northwards from a black smoker at the sea floor (from Bohrmann et al. 2023).

Guided by unmistakable plume signatures of the hydrothermal vents in the water column, we conducted a total of seven dives with ROV QUEST to record the fluid emission sites, their manifestations at the seafloor, and their distribution within the area (Figure 1C). A black smoker was found on the edge of an ~20-m-wide and 6 to 8-m-high mound that is composed primarily of debris from hydrothermal precipitates. Thin section analyses of the smoker chimney revealed that it is composed of Fe-Cu sulfide, mainly chalcopyrite (CuFeS_2), cubanite (CuFe_2S_3), and a phase with intermediate composition ($\text{Cu}_2\text{Fe}_3\text{S}_6$, ISS=intermediate solid solution). Also abundant are sphalerite and anhydrite, while pyrrhotite is a minor phase. The sphalerite in all samples has high contents of Fe (around 20 mol.%). The mineralization with pyrrhotite, cubanite, and Fe-rich sphalerite is indicative of rather low sulfur fugacities, which can be explained by high ratios of H_2 to H_2S in the venting fluids ($\text{H}_2(\text{aq}) + \frac{1}{2} \text{S}_2(\text{g}) = \text{H}_2\text{S}(\text{aq})$), however, these gases were not measured onboard the vessel. The occurrence of carbonate phases along the commonly observed sulfate minerals is due to the high alkalinity and the high pH value of the vent fluids. AUV exploration located several additional mounds to the south of the black smoker, two of which also exhibited active hydrothermal venting. The mound at the Nidhogg vent site at a water depth of 3031 m, and 300 m southwest of the black smoker is 10 m high and 30 m across. Several small chimneys are situated at the peak of the mound, one of which was intensively inhabited by amphipods. They serve as outlets of shimmering water, which, at one location, were measured to be at a temperature of 33°C.

The mound at the Yggdrasil vent site, which is situated about 140 m southwest of the Nidhogg vent site, is 30 m in diameter and 7 m high. Numerous chimneys and flange-structure on top of the mound issue vigorous flow of clear, shimmering fluids, which exhibit temperatures up to 272°C, i. e. significantly higher than at the Nidhogg vent site. Precipitates at the Yggdrasil vent site consist of pyrrhotite, Fe-Cu sulfides, sphalerite, galena, and anhydrite.

Based on the observed fluid chemistry and paragenesis of the hydrothermal precipitates at both black smoker and Yggdrasil sites, the circulating fluids likely had an intensive exchange with very thick sediment deposits. This, in turn, suggests an intense interaction of some ridge magmas with the Plio-Pleistocene sediments of the Svalbard continental margin. During this exchange, a large amount of thermogenic methane is formed, which could be detected in high concentrations in the plume of the Jøtul field. Our study therefore shows that high hydrocarbon seafloor emissions generated by hydrothermalism are not only related to sediment-covered basins such as the Guaymas Basin, the Okinawa Trough, or the Escanaba Trough, but can also to be expected along narrow ultraslow-spreading ridge systems such as the Knipovich Ridge.

Acknowledgements

We acknowledge the excellent and friendly support from the ship's crew of MSM109 in all areas (nautical, WTD, deck crew, engine and service area, etc.), from the shipping company as well as the employees of the "German Research Fleet Coordination Centre" in Hamburg and at MARUM logistics in Bremen. We thank both teams of the MARUM ROV and AUV and all technicians and student helpers, without whose contributions we would not have reached our scientific goals. The ship time of R/V MARIA S. MERIAN was provided by Deutsche Forschungsgemeinschaft; additional funding came from the Bremen Cluster of Excellence EXC 2077/0 "The Ocean Floor – Earth's Uncharted Interface". We also thank the Norwegian Petroleum Directorate in Stavanger for supporting the planning of the cruise.

References

- German CR, et al., Volcanically hosted venting with indications of ultramafic influence at Aurora hydrothermal field on Gakkel Ridge. *Nature Communications* 2022, 13, 6517.
- Pedersen RB, et al. Discovery of a black smoker vent field and vent fauna at the Arctic Mid-Ocean Ridge. *Nature Communications* 1, 126 (2010).

Scientific Output

List of Publications

Bohrmann G, Streuff K, Römer M, Knutsen SM, Smrzka D, Kleint J, Röhler A, Pape T, Sandstål NR, Kleint C, Hansen C, dos Santos Ferreira C, Walter M, de Paula Santos GM & Bach W, Discovery of the first hydrothermal field along the 500-km-long Knipovich Ridge offshore Svalbard (the Jøtul field), Scientific Reports 2024, 14(1), doi:10.1038/s41598-024-60802-3.

List of conference presentations

2025 | Venting induced by magma-sediment interaction at Jøtul field – first discovery of hydrothermal seafloor venting along the 500-km-long Knipovich spreading ridge. Talk during the GeoBerlin DGGV conference

2023 | Hydrothermal vents at Knipovich Ridge – the Jøtul Field and other recent discoveries of R/V Maria S. Merian cruise MSM109. Talk during the MarexKus workshop, Roma, Italy

2025 | The Jøtul hydrothermal field: High H₂ production in sediment-hosted hydrothermal vent fluids at an ultraslow spreading mid-ocean ridge. Talk during the Geo4Göttingen conference, Germany

Data

A total of 6 data sets have so far been stored in the PANGAEA database related to the MSM109 expedition. Data sets in PANGAEA will be expanded in parallel with further publications.

Master track:

<https://doi.org/10.1594/PANGAEA.950205>

Continuous thermosalinograph oceanography along RV MARIA S. MERIAN cruise track MSM109:

<https://doi.org/10.1594/PANGAEA.950202>

Sediment echosounder raw data (Atlas Parasound P70 echosounder entire dataset) of RV MARIA S. MERIAN during cruise MSM109:
<https://doi.org/10.1594/PANGAEA.959613>

Water column raw data (Kongsberg EM 122 entire dataset) of RV MARIA S. MERIAN during cruise MSM109:
<https://doi.org/10.1594/PANGAEA.955507>

Multibeam bathymetry raw data (Kongsberg EM 122 entire dataset) of RV MARIA S. MERIAN during cruise MSM109:
<https://doi.org/10.1594/PANGAEA.955497>

Composition of fluids collected at the Jøtul hydrothermal field, Knipovich Ridge, Arctic Mid-Ocean Ridge, MARIA S. MERIAN cruise MSM109:
<https://doi.org/10.1594/PANGAEA.966848>

Cruise Report

MSM109: https://doi.org/10.48433/cr_msm109

MSM110

East Greenland Cruise MSM110

Authors

Hereon Helmholtz Centre | Geestacht, Germany

H. Thomas

and MSM110 scientific party



Figure 1: MSM110 Scientific party.

The MSM110 research expedition with the research vessel Maria S. Merian took place in August 2022 as part of the HORIZON 2020 project ECOTIP. The aim of the project is to investigate potential tipping points and ecological cascades in Arctic marine ecosystems that may be caused by climatic and anthropogenic changes – rising temperatures, increasing freshwater inflow, and changes in physical-chemical boundary conditions.

The expedition focused on three fjord systems on the east coast of Greenland, which are characterized by different climatic, hydrographic, and ecological properties and thus form a gradient system from subarctic to high-arctic environments.

The study area covers the shelf region, which is strongly influenced by the East Greenland Current and is covered by sea ice for up to ten months of the year. The fjords – Scoresby Sound, Ardencaple Fjord, and Kong Oskar Fjord – offer ideal conditions for recording changes in hydrography, productivity, and biodiversity in a region where the effects of climate change are among the most severe in the world.

The voyage followed a north-south transect and included a total of nine 24-hour stations as well as numerous additional water and sediment stations. The work began in the Denmark Strait overflow area and continued along the Greenland coast to Dove Bay in the north. Extensive physical, chemical, biological, and geological data sets were collected at all main stations. These included CTD profiles, water samples for nutrients, trace elements, carbon parameters, radium isotopes, Hg species, and amino acids, plankton nets, in-situ pumps, multi-nets, and sediment sampling using box, mini, and gravity corers.

Particular focus was placed on linking meltwater dynamics, water mass properties, and biological processes. Extreme gradients were documented in Ardencaple Fjord, including surface samples with almost pure meltwater ($SP \approx 4$). In addition, samples were obtained in fjord areas with limited ship access using the onboard Zodiac. The sediment cores form an essential basis for paleoecological analyses to reconstruct hydrographic development since the last deglaciation. Initial geochemical and micropaleontological evaluations are already underway and will contribute to the creation of age models and the identification of climate and ecosystem changes in the long term.

Hydroacoustics (multibeam, parasound) enabled precise characterization of topography and sediment structures and supported optimal positioning of sediment drilling. A total of approximately 3,400 km of acoustic data was collected. In addition, microplastic samples were systematically taken in this region for the first time. Initial laboratory analyses show remarkably high concentrations, dominated by PET particles, which indicate previously underestimated transport routes via sea ice and currents and underscores the role of the Arctic as a potential secondary source. Other focal points included microbiological investigations (e. g., prokaryote abundances, FISH), analyses of dissolved amino acids, and the creation of a comprehensive metagenome dataset, which will be combined with metaproteomes in the future to record the functional properties of microbial communities. The evaluation of these datasets is currently ongoing.

Of particular note are the measured microplastic concentrations, which ranged between $1.0 \pm 0.8 \text{ L}^{-1}$ and $12 \pm 4 \text{ L}^{-1}$ for particles in the 20–500 μm range, depending on the station. The highest values were measured at the mouth of the Kangertittivaq (Scoresby Sound) near Ittoqqortoormiit.

Polyethylene terephthalate (PET) was the dominant polymer type, accounting for an average of 96%. Surprisingly, polylactic acid (PLA) was the second most common type of plastic, accounting for 1.6% – probably the highest proportion of PLA measured in marine samples to date. The findings suggest that ocean currents and sea ice transport play a greater role in the distribution of microplastics than previously thought. The Arctic Ocean could even act as a secondary source of microplastics in the North Atlantic via the East Greenland Current (EGC). Repeat sampling proved important as it revealed significant temporal variations in microplastic distribution.

The expedition was successful despite challenging ice and weather conditions at times. All three fjord systems were fully investigated; the data obtained provide a unique basis for assessing current and future climate influences on Arctic coastal ecosystems. They contribute significantly to a better understanding of tipping point mechanisms, changes in productivity and biodiversity, and potential consequences for ecosystem services and Arctic communities.

Scientific Output

List of Publications

Vetter CB, Hildebrandt L, Zimmermann T, Schmidt CE, Gareb FEL, Mitrano DM, Pröfrock D & Thomas H, Analysis of microplastics in the fjords of Tunu (East Greenland)., *Mar. Poll. Bull.* 2025, 38, 218, 118192, <https://doi.org/10.1016/j.marpolbul.2025.118192>.

Asiedu DA, Jónasdóttir S, Søndergaard J, Thomas H, Hempel N & Koski M, Mercury bioaccumulation and assimilation in marine plankton in meltwater influenced fjords and shelf waters along the east coast of Greenland., *Environmental Pollution* 2025, 366, 125473, doi: 10.1016/j.envpol.2024.125473.

Data

Cruise data:
<https://doi.pangaea.de/10.1594/PANGAEA.965754>

Cruise Report

MSM110: https://doi.org/10.48433/cr_msm110

MSM111

Deep drilling in the Baffin Bay for marine sediment records of Greenland Ice Sheet collapse during past warm intervals

Authors

MARUM, University of Bremen | Bremen, Germany

M. Kučera, J. C. Faust, J. Meilland, R. Morard, V. Diekamp, M. Siccha, M. Bergenthal

University of Bremen | Bremen, Germany

T. von Dobeneck, K. Streuff

GEOTOP, Université du Québec à Montréal | Montréal, Canada

A. de Vernal

Tübingen University | Tübingen, Germany

H. Schulz

Aarhus University | Aarhus, Denmark

H. Detlef

Rationale and Aims of the Expedition MSM111

The ongoing accelerated melting of Greenland Ice Sheet (GIS) raises concerns about the future of this large meltwater source under further global warming. Indirect evidence from the magnitude of past sea-level high stands and numerical modelling suggests that the GIS was significantly reduced during MIS5 and largely collapsed during MIS11 (Dutton et al., 2015). This is a source of concern under projected future climate change scenarios, due to the resulting discharge of large amounts of meltwater to the North Atlantic, sea-level rise, and the establishment of a fundamentally different landscape on Greenland. MIS11 was characterized by insolation-driven long climatic optimum, which resulted in a protracted sea level rise lagging global temperature by ~5 ka and culminating in a sea-level highstand around 400 ka (Milker et al., 2013). At the same time, the emergence of tree pollen (de Vernal & Hillaire-Marcel, 2008) and provenance change in glaciogenic

debris (Reyes et al., 2014) in marine sediments off southwest Greenland indicate a regime shift, consistent with a large-scale ice-sheet collapse. Indeed, material recovered from the bottom of boreholes that penetrated throughout the present ice sheet contains plant fossils and ancient DNA indicative of a vegetated Greenland interior (Christ et al., 2021; Willerslev et al., 2007).

Whilst the existence of a collapse of the GIS and vegetation of Greenland at some point in the Quaternary, is well established, the exact timing and relationship with global and local climatic forcing are not well constrained, and the recurrence pattern of the likely multiple ice-free periods is completely unknown (Christ et al., 2021). The most dynamic portions of the GIS discharge into the Baffin Bay, but so far, no record has been recovered from this key region to reconstruct the history of the GIS collapse during late Pleistocene. Such record could potentially help to constrain both the pattern and chronology of GIS collapse, as well as the phase relationship of oceanic change in the Baffin Bay and the collapse of the North American Arctic Ice Sheets.

The only investigations of paleoenvironmental change in the Baffin Bay prior to 100 ka are based on micropaleontological studies from ODP Site 645 (Baldauf et al., 1989). Unfortunately, the core recovery was poor, providing only a discontinuous record across the target interval (Aksu, 1983). Based on biostratigraphic data, the Pliocene to Quaternary transition could be positioned at about 150 m in the sedimentary sequence. This indicates that it should be possible to obtain a continuous sediment sequence from the Baffin Bay since MIS11 by drilling to a depth of 100 m. Hence, the **principle aim** of the MSM111 expedition was to make use of the unique capacity of the MeBo-200 drill rig to recover a continuous sediment sequence from the central Baffin Bay to reconstruct changing oceanic conditions and terrigenous sediment supply from Greenland and Arctic ice sheets throughout the late Quaternary.

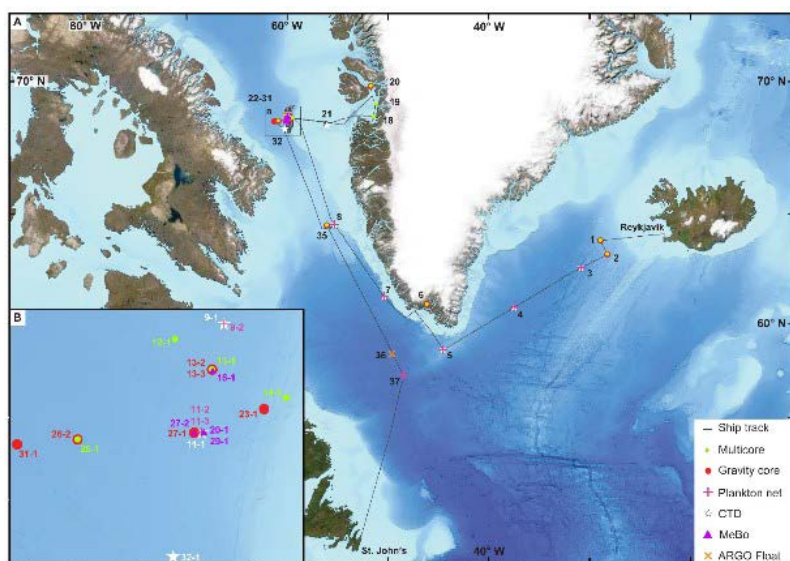


Fig. 1: Track of R/V Maria S. Merian Cruise MSM111. B) details the operational area of MeBo-200.

Figure 1: Track of R/V Maria S. Merian Cruise MSM111. B) details the operational area of MeBo-200.

To make the most of the transit to and from the Baffin Bay, and to provide an alternative program in case of bad weather or technical difficulties, the **ancillary aim** of the cruise was to obtain plankton and sediment material for plankton ecology research, calibration of palaeoceanographic proxies and reconstruction of oceanic conditions and biotic response since the last ice age. To this end, plankton nets taken along the cruise track were used to obtain plankton samples for analyses of genetic diversity and biotic associations of planktonic foraminifera, and their living cells were collected for cultivation experiments. Moreover, multicorer deployments and gravity cores off Iceland and in Greenland Fjord settings were used to obtain surface sediments for calibration of organic and inorganic geochemical and micropaleontological proxies and environmental and ancient sedimentary DNA survey (Figure 1).

Results of the Expedition MSM111

The main working area of the cruise, located on the continental slope off Disko Bay, was extensively surveyed by multibeam bathymetry and sediment echo sounder profiles. The bathymetry revealed a generally flat topography with some slope-cutting depressions, providing evidence for concentrated down-slope processes, and a series of slope-parallel grooves at depths around 1000 m that were previously interpreted as giant iceberg ploughmarks. At greater depths, the survey revealed a smooth seafloor, indicative of typical basin-fill sedimentation.

The seafloor was characterized by excellent acoustic penetration, leading to good resolution of the upper 40-70 m, with some reflections recovered from depths below 100 m (Figure 2). Throughout, the acoustic character of the seafloor is defined by smooth, perfectly stratified reflectors, which appear continuous over long distances and are characterized by homogenous amplitudes, likely reflecting regular changes between the deposition of hemipelagic muds, and coarser sediments, such as sands or ice-rafted debris.

In the absence of data from the outer Disko Bay fan reaching beyond the last glacial age (Jackson et al., 2017, Knutz et al., 2011, Simon et al., 2014), the position of the MeBo drilling sites was determined on the basis of the acoustic profiles and a transect of multicorer and gravity cores taken across the slope. The primary target of the drilling was to penetrate the apparent regional unconformity underlying the acoustically transparent and well resolved sediment package with a thickness of about 70 m in the upper part of the slope at water depth of about 1400 m. To this end, a total of four MeBo drilling sites were sited and realized. The first drilling revealed an upper sediment package containing an alteration of unconsolidated muds and fine sands, which were highly water-saturated and difficult to core. Therefore, subsequent drilling attempted to bypass the upper sediment package and begin coring at greater depth. This was successful and the four MeBo drill holes penetrated between 53 and 126 m below the seafloor and facilitated the recovery of two borehole logs (92 m and 123 m).

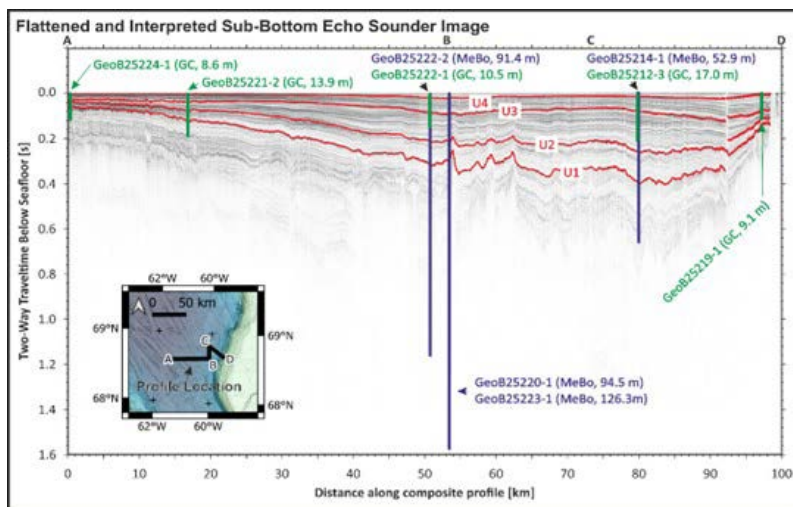


Figure 2: Flattened and interpreted sub-bottom echo sounder profile across the outer Disko Bay fan with the position of all four MSM 111 MeBo-200 drill holes (blue) and selected gravity cores (green).

The prerequisites for the interpretation of the Disko Bay fan sediment series are the development of an age model and a thorough characterization of the physical

and chemical properties of the recovered sediment sequence. To this end, the 133 m of recovered MeBo cores, together with additional 68 m of sediment recovered from six gravity cores across the slope transect were subjected to physical properties logging, magnetic susceptibility measurements, 3D CT scanning and XRF analyses. These analyses have been largely completed and allowed a characterization of the sedimentary facies of the Disko Bay fan. The first step in the age model development comprised high-resolution paleomagnetic investigation of the MeBo cores and a long gravity core located downslope. These data revealed that all recovered sediments belong to the Brunhes chron. Further investigations including the interpretation of paleomagnetic intensity records, data from optically stimulated luminescence, and radiogenic isotopes are still ongoing. Critical for the interpretation of the stratigraphy and depositional history is the development of an integrated stratigraphic network, tying individual cores to an interpreted acoustic profile perpendicular to the slope. This work is largely completed and will be presented during the conference.

Next to the still ongoing work on the long sediment records, the ancillary program of the cruise has progressed significantly. Observations from plankton tows and subsequent cultivation experiments onboard led to a major breakthrough in our understanding of the lifecycle of planktonic foraminifera (Meilland et al., 2024). A sediment core from the Narsaq Fjord yielded a continuous record of Holocene ice sheet retreat and subsequent hydroclimate variability, including during the period of the Norse settlement of Greenland and a long gravity core record from the Disko Bay slope yielded a very -high resolution reconstruction of sea-ice conditions since the MIS3. These results will be highlighted in separate poster presentations.

References

Aksu AE, Holocene and Pleistocene Dissolution Cycles in Deep-Sea Cores of Baffin-Bay and Davis Strait – Paleo-Oceanographic Implications, *Marine Geology* 1983, 53(4), 331–348.

Baldauf JG, Clement B, Aksu AE, de Vernal A, et al., Magnetostratigraphic and biostratigraphic synthesis of ocean drilling program leg 105: Labrador Sea and Baffin Bay, *Proceedings of the Ocean Drilling Program: scientific results* 1989, 105, 935–956.

Christ AJ, Bierman PR, Schaefer JM, Dahl-Jensen D, et al., A multimillion-year-old record of Greenland vegetation and glacial history preserved in sediment beneath 1.4 km of ice at Camp Century, *Proceedings of the National Academy of Sciences of the United States of America* 2021, 118(13), e2021442118.

de Vernal A & Hillaire-Marcel C, Natural variability of Greenland climate, vegetation, and ice volume during the past million years, *Science* 2008, 320(5883), 1622–1625.

Dutton A, Carlson AE, Long AJ, Milne GA, et al., Sea-level rise due to polar ice-sheet mass loss during past warm periods, *Science* 2015, 349(6244), aaa4019.

Jackson R, Carlson AE, Hillaire-Marcel C, Wacker L, et al., Asynchronous instability of the North American-Arctic and Greenland ice sheets during the last deglaciation, *Quaternary Science Reviews* 2017, 164, 140–153.

Knutz PC, Sicre MA, Ebbesen H, Christiansen S & Kuijpers, A, Multiple-stage deglacial retreat of the southern Greenland Ice Sheet linked with Irminger Current warm water transport, *Paleoceanography* 2011, 26, PA3204.

Milker Y, Rachmayani R, Weinkauff M F G, Prange M, et al., Global and regional sea surface temperature trends during Marine Isotope Stage 11, *Climate of the Past* 2013, 9(5), 2231–2252.

Simon Q, Hillaire-Marcel C, St-Onge G & Andrews JT, North-eastern Laurentide, western Greenland and southern Innuitian ice stream dynamics during the last glacial cycle, *Journal of Quaternary Science* 2014, 29(1), 14–26.

Willerslev E, Cappellini E, Boomsma W, Nielsen R, et al., Ancient biomolecules from deep ice cores reveal a forested Southern Greenland, *Science* 2007, 317(5834), 111–114.

Scientific Output

List of Publications

Meilland J, Siccha M, Morard R & Kucera, M, Continuous reproduction of planktonic foraminifera in laboratory culture, *Journal of Eukaryotic Microbiology* 2024, 71, e13022, doi:10.1111/jeu.13022.

Theses

Janßen A, Usage of IP25 biomarker as indicator of fjord sea-ice coverage in the age of the Norse Greenlanders, 2025, BSc Thesis, Faculty of Geosciences, University of Bremen.

Mukherjee S, Identifying sedimentary facies using X-Ray CT, XRF, Paleomagnetic and Parasound to associate two sediment cores from Central Baffin Bay, 2025, MSc Thesis, Faculty of Geosciences, University of Bremen.

Song X, Paleomagnetic investigation of sedimentary cores GeoB25220-1 and GeoB25223-1 from Baffin Bay recovered during MSM-111, 2023, BSc Thesis, Faculty of Geosciences, University of Bremen.

List of conference presentations

2025 | **Sea ice and ice sheet dynamics in southeastern Baffin Bay from Late MIS 3 to Early Holocene: a high-resolution biomarker study**, PalaeoArc Conference, Tromsø, Norway.

2025 | **Identifying sedimentary facies using X-Ray CT, XRF, Paleomagnetic and Parasound to associate two sediment cores from Central Baffin Bay**, PalaeoArc Conference, Tromsø, Norway.

2025 | **Fjord sediments in southern Greenland reveal Holocene glacial activity and organic carbon sequestration dynamics**, EGU Conference, Vienna, Austria.

2024 | **Investigating Greenland Ice Sheet collapses during past warm intervals – A chronostratigraphic challenge**, ArcSTRAT – The Arctic Ocean Stratigraphic and Paleoclimate Conference, Tromsø, Norway.

2024 | **Chronostratigraphy of glaciomarine sediments off the West Greenland Shelf: a key to the understanding of the Quaternary evolution of the Greenland ice sheet**, EGU Conference, Vienna, Austria

2024 | **Sea-ice conditions during the Late Pleistocene and Holocene in Baffin Bay: insights from biomarker lipids**, PalaeoArc Conference, Stockholm, Sweden.

2024 | **Holocene to Eemian sea ice and terrigenous influx variations in Baffin Bay – a lipid biomarker study**, EGU Conference, Vienna, Austria.

2023 | **Deep drilling in the Baffin Bay: Investigating Greenland Ice Sheet collapse during past warm intervals**, Greenland Ice Sheet Stability: Lessons from the Past, Bergen, Norway.

2023 | **Deep drilling in the Baffin Bay: Investigating Greenland Ice Sheet collapse during past warm intervals**, ECORD Summer School, Bremen, Germany.

Data

Physical oceanography during RV MARIA S. MERIAN cruise MSM111 BAFFDEEP (2023):
<https://doi.org/10.1594/PANGAEA.960017>

Processed MPS-mounted CTD data from Maria S. Merian cruise MSM111 BAFFDEEP (2024):
<https://doi.org/10.1594/PANGAEA.973212>

Master track of Maria S. Merian cruise MSM111 in 1 sec resolution (zipped, 14.6 MB) (2022):
<https://doi.org/10.1594/PANGAEA.952940>

Water content of sediment core GeoB25213-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983248>

Water content of sediment core GeoB25221-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983263>

Water content of sediment core GeoB25226-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983269>

Water content of sediment core GeoB25217-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983329>

Water content of sediment core GeoB25201-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983225>

Water content of sediment core GeoB25212-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983252>

Water content of sediment core GeoB25216-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983260>

Water content of sediment core GeoB25211-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983245>

Water content of sediment core GeoB25206-2, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983160>

Water content of sediment core GeoB25215-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983255>

Water content of sediment core GeoB25206-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983226>

Continuous thermosalinograph oceanography along RV MARIA S. MERIAN cruise track MSM111 (2023):
<https://doi.org/10.1594/PANGAEA.958392>

Master tracks in different resolutions of Maria S. Merian cruise MSM111, Reykjavik – St. John's, 2022-09-02-2022-10-04 (2022):
<https://doi.org/10.1594/PANGAEA.952943>

Magnetic volume susceptibility of 12 gravity cores from RV MARIA S. MERIAN cruise MSM111 (2025):
<https://doi.org/10.1594/PANGAEA.984008>

CT raw data (DICOM format) of sediment core GeoB25217-2, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.982974>

CT raw data (DICOM format) of sediment core GeoB25220-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.982979>

CT raw data (DICOM format) of sediment core GeoB25224-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.982992>

CT raw data (DICOM format) of sediment core GeoB25212-3, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.982965>

CT raw data (DICOM format) of sediment core GeoB25221-2, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.982983>

CT raw data (DICOM format) of sediment core GeoB25206-2, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.982944>

CT raw data (DICOM format) of sediment core GeoB25214-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.982966>

CT raw data (DICOM format) of sediment core GeoB25223-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.982991>

Multibeam bathymetry raw data (Kongsberg EM122 entire dataset) of RV MARIA S. MERIAN during cruise MSM111 (2023):
<https://doi.org/10.1594/PANGAEA.953855>

Water column raw data (Kongsberg EM122 entire dataset) of RV MARIA S. MERIAN during cruise MSM111 (2023):
<https://doi.org/10.1594/PANGAEA.953856>

Electrical conductivity, porosity and density of 12 gravity cores from RV MARIA S. MERIAN cruise MSM111 (2025):
<https://doi.pangaea.de/10.1594/PANGAEA.984159>

X-ray fluorescence (XRF) core scanner raw data of sediment core GeoB25206-2, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983542>

X-ray fluorescence (XRF) core scanner raw data of sediment core GeoB25220-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983625>

X-ray fluorescence (XRF) core scanner raw data of sediment core GeoB25222-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983629>

X-ray fluorescence (XRF) core scanner raw data of sediment core GeoB25212-3, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983599>

X-ray fluorescence (XRF) core scanner raw data of sediment core GeoB25223-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983636>

X-ray fluorescence (XRF) core scanner raw data of sediment core GeoB25217-2, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983602>

X-ray fluorescence (XRF) core scanner raw data of sediment core GeoB25219-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983622>

X-ray fluorescence (XRF) core scanner raw data of sediment core GeoB25214-1,
MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983601>

X-ray fluorescence (XRF) core scanner raw data of sediment core GeoB25221-2,
MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983626>

X-ray fluorescence (XRF) core scanner raw data of sediment core GeoB25222-2,
MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983630>

X-ray fluorescence (XRF) core scanner raw data of sediment core GeoB25224-1,
MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983637>

Visual core description and line scanner images of sediment core GeoB25206-2,
MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983000>

Visual core description and line scanner images of sediment core GeoB25219-1,
MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983042>

Visual core description and line scanner images of sediment core GeoB25220-1,
MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983043>

Visual core description and line scanner images of sediment core GeoB25212-3,
MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983001>

Visual core description and line scanner images of sediment core GeoB25222-1,
MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983074>

Visual core description and line scanner images of sediment core GeoB25222-2,
MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983085>

Visual core description and line scanner images of sediment core GeoB25223-1,
MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983115>

Visual core description and line scanner images of sediment core GeoB25224-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983123>

Visual core description and line scanner images of sediment core GeoB25214-1, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983010>

Visual core description and line scanner images of sediment core GeoB25217-2, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983026>

Visual core description and line scanner images of sediment core GeoB25221-2, MARIA S. MERIAN cruise MSM111:
<https://doi.pangaea.de/10.1594/PANGAEA.983055>

Electrical conductivity, porosity and density of sediment core GeoB25202-2 (2025):
<https://doi.pangaea.de/10.1594/PANGAEA.984140>

Electrical conductivity, porosity and density of sediment core GeoB25206-2 (2025):
<https://doi.pangaea.de/10.1594/PANGAEA.984144>

Electrical conductivity, porosity and density of sediment core GeoB25212-2 (2025):
<https://doi.pangaea.de/10.1594/PANGAEA.984145>

Electrical conductivity, porosity and density of sediment core GeoB25217-2 (2025):
<https://doi.pangaea.de/10.1594/PANGAEA.984147>

Electrical conductivity, porosity and density of sediment core GeoB25219-1 (2025):
<https://doi.pangaea.de/10.1594/PANGAEA.984148>

Magnetic susceptibility of sediment core GeoB25201-3 (2025):
<https://doi.org/10.1594/PANGAEA.983974>

Magnetic susceptibility of sediment core GeoB25206-2 (2025):
<https://doi.org/10.1594/PANGAEA.983992>

Magnetic susceptibility of sediment core GeoB25212-3 (2025):
<https://doi.org/10.1594/PANGAEA.983999>

Magnetic susceptibility of sediment core GeoB25221-2 (2025):
<https://doi.org/10.1594/PANGAEA.984003>

Magnetic susceptibility of sediment core GeoB25219-1 (2025):
<https://doi.org/10.1594/PANGAEA.984009>

Electrical conductivity, porosity and density of sediment core GeoB25222-1 (2025):
<https://doi.pangaea.de/10.1594/PANGAEA.984150>

Electrical conductivity, porosity and density of sediment core GeoB25226-2 (2025):
<https://doi.pangaea.de/10.1594/PANGAEA.984156>

Magnetic susceptibility of sediment core GeoB25202-2 (2025):
<https://doi.org/10.1594/PANGAEA.983991>

Magnetic susceptibility of sediment core GeoB25212-2 (2025):
<https://doi.org/10.1594/PANGAEA.983996>

Magnetic susceptibility of sediment core GeoB25224-1 (2025):
<https://doi.org/10.1594/PANGAEA.984006>

Magnetic susceptibility of sediment core GeoB25226-1 (2025):
<https://doi.org/10.1594/PANGAEA.984007>

Electrical conductivity, porosity and density of sediment core GeoB25201-3 (2025):
<https://doi.pangaea.de/10.1594/PANGAEA.984131>

Electrical conductivity, porosity and density of sediment core GeoB25212-3 (2025):
<https://doi.pangaea.de/10.1594/PANGAEA.984146>

Electrical conductivity, porosity and density of sediment core GeoB25221-2 (2025):
<https://doi.pangaea.de/10.1594/PANGAEA.984149>

Magnetic susceptibility of sediment core GeoB25201-2 (2025):
<https://doi.org/10.1594/PANGAEA.983973>

Magnetic susceptibility of sediment core GeoB25217-2 (2025):
<https://doi.org/10.1594/PANGAEA.984000>

Magnetic susceptibility of sediment core GeoB25222-1 (2025):
<https://doi.org/10.1594/PANGAEA.984004>

Electrical conductivity, porosity and density of sediment core GeoB25201-2 (2025):
<https://doi.pangaea.de/10.1594/PANGAEA.984114>

Electrical conductivity, porosity and density of sediment core GeoB25224-1 (2025):
<https://doi.pangaea.de/10.1594/PANGAEA.984155>

Cruise Report

MSM111: https://doi.org/10.48433/CR_MSM111

MSM112

The Rio Magdalena Delta ROFI system – Land-Sea Interaction of the major tributary of the Caribbean Sea

Authors

Kiel University | Kiel, Germany

C. Winter, F. Arévalo Meza, R. Barrett, M. Becker, G. A. Diaz Mendoza, G. Herbst, G. A. v. Rönn, J. Gottschalk

Heidelberg University | Heidelberg, Germany

Y. Rojas Agramonte, E. Villanueva Garcia

Leibniz-Institute for Baltic Sea Research Warnemünde | Warnemünde, Germany

P. Holtermann

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

O. Keshk, S. Sander

Universidad de Norte | Barranquilla, Colombia

Ó Álvarez-Silva, R. Torres Parra

Universidad del Atlántico | Atlántico, Colombia

A. Gracia Clavijo

Universidad Nacional de Colombia | Medellin, Colombia

G. Bernal Franco, A. Osorio Arias

Universidad de Antioquia | Medellin / Turbo, Colombia

M. Zambrano Ortiz, J. M. Riascos

Ecopetrol | Piedecuesta, Colombia

D. Rincón Martinez, J. Naranjo Vesga

Abstract

The Magdalena River mouth in the Colombian Caribbean Sea is a prominent example of a large ROFI (region of fresh-water influence) system in the tropics.

The expedition MSM112 (07.10.2022–14.11.2022 St John's to Cartagena) focused on the geophysical, sedimentological, and biogeochemical processes of the delta and ROFI, and searched for connections of the river mouth to the La Guajira upwelling system. We combined ship-based hydro-acoustic methods, direct sampling (sediment and water column) on specified transects, and sea floor observations with an autonomous sea floor observatory (lander) at selected stations. Several stations with different morphological, sedimentological, and biogeochemical characteristics were explored. We measured the extent, composition, and dynamics of the river plume: i. e. the instantaneous dimensions, stability, mixing conditions, and structure of the fresh water plume, as well as total suspended solids, pycnocline dynamics, and turbulent processes. We mapped three canyon systems offshore the Colombian Caribbean coast with parasound and multi beam echo sounder, and took gravity cores and box cores at representative positions. Further we derived data to quantify modern sedimentary connections between the river mouth, canyon systems, and adjacent coastal zones. We also explored the hypothesis of a possible interaction between the RM ROFI and La Guajira Upwelling system by taking water samples and additional sediment samples in that region.

Work Area

The Magdalena River plays a key role in the hydrodynamic, morphodynamic and biochemical processes of the Caribbean Sea and stands as a prominent example of a tropical river mouth and delta system. This river is the largest confluent to the Caribbean Sea with an average runoff of $\sim 205.5 \text{ km}^3/\text{a}$, equivalent to 26% of the total fluvial discharge into this ocean basin, forming an extended Region of Freshwater Influence (ROFI). It is thus of influence to the Gulf of Mexico water masses and loop current through the Caribbean Current (CC) which is forced to split into two sections when it reaches the Nicaragua Rise: One section flows to the the Loop current and the second enters the Panamá- Colombian Gyre (PCG). The river discharge, wind driven currents, (CC, Panamá-Colombia counter current, PCG), mesoscale eddies and the La Guajira upwelling system are the predominant natural forcings that modulate the region, generating complex hydrodynamics, sedimentary pathways and depositional patterns along the Colombian Caribbean coast, shelf, and submarine fan system. Human interventions on coastal and riverine systems play an important role in recent sediment transport and balance in the region.

The Magdalena River has a length close to 1,600 km and its basin covers an area of approximately 257,440 km^2 , corresponding to 24% of the total area of Colombia, where 80% of the population lives, 85% of economic activity is carried out, receiving more than 500 rivers and numerous streams. It discharges into the Caribbean Sea, at the site known as Bocas de Ceniza, at $11^\circ 06' \text{ N}$ and $74^\circ 51' \text{ W}$.

The Canal del Dique also serves as a tributary to its waters, which reach the sea in the bay of Cartagena. A unimodal annual cycle characterizes the runoff of the river, with lowest discharges in February-March and highest discharges in October-November, when the ROFI reaches its maximum extension.

In a greater scale, the Magdalena River discharge accounts for the temperature and salinity of the Caribbean surface water, and -together with the Guajira upwelling modulates the seasonal sea level cycle in the South Caribbean Sea. Today, most of the North Atlantic's subtropical gyre water circulates through the Caribbean Sea towards the Gulf of Mexico where the Loop current is formed and joins the Gulf stream. Being the most important freshwater source of the Caribbean, Rio Magdalena thus affects the salinity and density structure of the Gulf of Mexico and the thermohaline circulation up to the North Atlantic. The discharged sediment load is $\sim 144 \times 10^6$ t/a, with suspended sediment concentration up to 11 g/l. Featuring these suspended sediment concentrations considered among the highest worldwide, the Magdalena system is also the main source of sediments to the Caribbean.

Aims

The Magdalena River stands as a prominent example for a large ROFI (Region Of Freshwater Influence) system in the tropics. Considering that important physical processes driving the land-sea interaction in tropical regions remain poorly understood and that tropical ROFIs are vulnerable systems explicitly prone to major reactions to climate change in the future, the Rio Magdalena River mouth, shelf, and submarine fan system were explored. The following aims guided the cruise:

- Assessment of the extension and dynamics of the sediment plume: We measured the dimensions, stability, extent, mixing conditions, structure of the salt wedge, total suspended solids (TSS), pycnocline dynamics, and turbulent processes.
- Study the architecture and (past) sedimentary processes of the submarine canyons off Rio Magdalena and the Santa Marta coast with a focus on human impact.
- Exploration of the hypothesis of a possible interaction between the RM ROFI and La Guajira Upwelling system.

We combined ship based hydroacoustic methods, direct sampling (sediment and water column) on specified transects, and sea floor observations with autonomous observatories (lander) at selected stations. Stations of different morphological,

sedimentological and biological characteristics were explored. As the sea floor structure and dynamics of the river mouth, prodelta and fan were mostly unknown, a large part of the cruise was of explorative nature, producing data for the scientific community for the first time.

Agenda

The joint expedition MSM112 “RioM ROFI” with the German research vessel MARIA S. MERIAN investigated geophysical, sedimentological, and biochemical land-sea interaction processes in the coastal and offshore waters of the Colombian Caribbean.

The cruise started in St. John's (Canada), where the containers with the scientific gear were loaded. The German team of scientists from CAU Kiel and IOW Warnemuende boarded and set off on October 6th, 2022. We sailed south for 12 days, through the Sargasso Sea, observing the fascinating loops of the Gulf Stream, which could be observed in the flow data of the hull mounted Acoustic Doppler Current Profiler (ADCP). After the passage between the Dominican Republic and Puerto Rico, we sailed through the Caribbean Sea, heading straight for Colombia.

We moored at the port of Cartagena for one day for boarding of the Colombian scientists of the participating institutions Universidad del Norte (Barranquilla), Universidad del Atlántico, Barranquilla, Universidad Nacional de Colombia (Medellín), Universidad de Antioquia (Turbo) and Centro de Innovación y Tecnología de Ecopetrol S.A. Also an observer for marine mammals and an inspector of the competent authority DIMAR joined the cruise. After a diplomatic reception on the quay and a VIP visit to the ship the actual research expedition started.

The first study area offshore the Rio Magdalena river mouth was reached on 20.10.: Here, submarine canyons, large slumps, and channel-levee systems are located in close proximity to the river mouth. We first used the hull mounted multibeam echo sounder and parametric echo sounder to survey the morphology and shallow subsurface of two submarine canyon systems. With the parametric echo sounder the structure of the seafloor was revealed. Profiles across the axis of the canyons were analysed to define suitable positions for sampling with box and gravity corers. We recovered several large box cores and gravity cores. The boxes were immediately processed and a large number of subsamples were collected for specific further processing in the corresponding laboratories.

An autonomous lander was deployed to the seafloor for almost two weeks to measure data on waves and current velocities, in-situ grain sizes and turbidity of the water column of the river mouth. In addition to the lander, the onboard

installed velocity meters (ADCP), the CTD probe, a towed catamaran with a measurement chain of sensors and a microstructure probe that was continuously winched up and down from the stern of the ship were used on transects and stations defined on the basis of satellite images.

After these a third canyon system was explored: The La Aguja Canyon, which cuts deep into the seafloor just in front of the impressive mountain range of the Sierra Nevada de Santa Marta. We performed a new, very detailed mapping of the seafloor by surveying with the multibeam echosounder and gained a good insight into the shallow subsurface by imaging with the parametric echosounder. The high-resolution bathymetry details the steep slopes, slumps, meanders, and corresponding sedimentary deposits that we tracked in a series of stations with large box cores and 10m gravity cores from the coast to the continental shelf.

The last week of the expedition MSM112 started in the waters off La Guajira, where a transect of CTD stations was defined from water depths of 2600m towards the shallow coastal waters. Also, here additional gravity cores and box cores were taken. At the mouth of the Rio Magdalena the sea floor observatory was recovered. The lander had been measuring for about two weeks at a depth of 30m and had recorded current profiles with several ADCPs, and also other water column properties. Based on the observations of the first week and more recent satellite imagery, we could optimize our measurement program of the last days accordingly. We again combined profile measurements in the plume with the shipboard installed ADCPs and by using the towed catamaran with various CTD and current sensors. At selected stations along and across the sediment plume, we collected water samples and determined the structure and nature of the sediment plume with microstructure probes, CTD, and LISST (in-situ particle sizer). The MSM112 research program ended with the last CTD station on the afternoon of Nov. 13, 2022, in the Rio Magdalena River mouth.

Outcome

The cruise has formed a well-connected group of researchers in Colombia and Germany. With high motivation based on the good quality of the data, and with the help of the bilateral project funding BMBF WtZ “Bilateral Cooperation in the Marine and Geosciences” (project 01DN23008) a series of workshops were held to communicate about the analyses, reports, and publications of data. Travels and student workers could be financed to support the post-cruise analyses and communications. Unfortunately, we yet could not acquire dedicated funding for the scientific analyses, and so all work on the data is done aside the normal duties of the involved scientists. This may slow down the process, but still leads to very interesting results: The cruise has been communicated in many news coverages. At different conferences and workshops results of the cruise have been presented

(see below). A number of scientific publications in international peer-reviewed journals are already published, or underway (see below) and several more are planned, based on preliminary results of the hydrodynamic and geological data. A DFG proposal on cruise data and an idea developed during the cruise has been submitted. The cruise has led to a Humboldt fellowship of Óscar Álvarez, which he spent at Kiel University in Germany.

Scientific Output

List of Publications

Naranjo-Vesga J, Mantilla O, Rincón-Martínez D, Rodríguez-Rubio E, Ortiz-Karpf A, Winter C & Rojas-Agramonte Y, The Guajira contourite depositional system along the northern Colombian Caribbean convergent margin, *Marine and Petroleum Geology* 2025, 182, doi:10.1016/j.marpetgeo.2025.107556.

Bernal G, Rincon-Martinez D, Barragán-Jacksson CM, Martínez G, Naranjo-Vesga J, Carreño A, Pacheco-Mendoza JY, Gutiérrez A, Benavides M, Gottschalk J & Winter C, Deep Sediments and Foraminifera Assemblages in the Tayrona Basin, Southern Caribbean 2025, SSRN, doi: /10.2139/ssrn.5360965.

Álvarez-Silva Ó, Becker M, Flores RP, Arévalo F, Holtermann P, Cardona Y & Winter C, The asymmetric hydrodynamic structure of a wind-dominated river plume, *JGR Oceans* (resubmitted).

Villanueva-García E, Rojas-Agramonte Y, Rincón-Martínez D, Idárraga-García J, Naranjo-Vesga J, Díaz-Mendoza JA, Riascos J, Rösel D, von Rönn GA, Carreño-Parra A & Winter C, Sediment transfer dynamics across an active continental margin revealed by geochronology and mineralogy: the Magdalena and La Aguja submarine canyons, northern Colombia, *Sedimentary Geology* (resubmitted).

Bernal G, Rincon-Martinez D, Barragán-Jacksson CM, Martínez G, Naranjo-Vesga J, Carreño A, Pacheco-Mendoza JY, Gutiérrez A, Benavides M, Gottschalk J & Winter C, Deep Sediments and Foraminifera Assemblages in the Tayrona Basin, Southern Caribbean, *Journal of Marine Systems* 2025 (resubmitted).

Torres-Parra R, Álvarez-Silva Ó, Cardona Y, Becker M, Holtermann P, Salón-Barros J & Winter C, Upper-Ocean Stratification in the Magdalena River ROFI Reveals a Shallow Buoyant Layer in the Southern Caribbean Sea, *Frontiers in Marine Science*, section Coastal Ocean Processes (resubmitted).

List of conference presentations

2023 | **Crucero Científico MSM112: El sistema ROFI del Delta del Río Magdalena. Análogo moderno para una margen convergente con alto aporte de sedimentos.** XIX Congreso Colombiano de Geología, VI Simposio de Exploradores

2024 | **Quantifying fluxes of microplastics from the Magdalena River into the Caribbean Sea.** Micro 2024: Plastic pollution from macro to nano. Lanzarote, Spain.

2025 | **Provenance of sediments offshore northern Colombia as evidenced by detrital zircon U-Pb study of modern sediments (Magdalena River Delta and La Aguja Canyon).** 37th International Geological Conference

2025 | **Sediment provenance from offshore northern Colombia: Detrital zircon U-Pb geochronology of the Magdalena River Delta and La Aguja Canyon,** EGU General Assembly 2025, Vienna

2025 | **From Artisanal to Industrial-Scale Gold Mining: Marine Mercury Contamination in Two Case Studies from the Global South.** Toxic Metals Symposium Munich

2025 | **Exploring the hydrodynamic structure of the Magdalena River plume in the Caribbean Sea.** Latin American Physics of Estuaries and Coastal Oceans conference – LAPECO, Puerto Varas, Chile

2025 | **Exploring the Rio Magdalena ROFI.** CliMetS Central and South America Workshop, Medellin, Colombia

2025 | **MSM112: Exploring the Rio Magdalena ROFI.** UNAL Workshop, Medellin, Colombia

2025 | **Offshore Sediment Provenance in Northern Colombia: The Role of Submarine Canyons,** CATEDRA EUROPA, Barranquilla, Colombia

2025 | **Sediment Provenance in Northern Colombia: The Role of Submarine Canyons,** UNAL Workshop, Medellin, Colombia

Data

Master tracks in different resolutions of Maria S. Merian cruise MSM112, St. John's – Cartagena, 2022-10-07–2022-11-14:

<https://doi.org/10.1594/PANGAEA.957646>

Water column raw data (Kongsberg EM712 entire dataset) of RV MARIA S. MERIAN during cruise MSM112:

<https://doi.org/10.1594/PANGAEA.965746>

Multibeam bathymetry raw data (Kongsberg EM712 entire dataset) of RV MARIA S. MERIAN during cruise MSM112:

<https://doi.org/10.1594/PANGAEA.965745>

Shipboard ADCP current measurements (75 kHz transit dataset) during RV MARIA S. MERIAN cruise MSM112:

<https://doi.org/10.1594/PANGAEA.964673>

Continuous thermosalinograph oceanography along RV MARIA S. MERIAN cruise track MSM112:

<https://doi.org/10.1594/PANGAEA.959030>

CTD dataset collected during the MSM112 cruise conducted in the Magdalena River plume, Colombia. October – November 2022:

https://doi.org/10.26640/cecoldo.dataset_00574

Others

Title: Rio Magdalena Land-Sea Interactions, 2023, Projektförderung zur Wissenschaftlich-Technologischen Zusammenarbeit (BMBF)/Movilidad Academica con Alemania (Minciencias), Project ID in Colombia: 94641CT80740-026-2023

Álvarez-Silva O, Title of the project: Exploring the region of freshwater influence (ROFI) of the Magdalena River in the Caribbean Sea: Following Humboldt's path, 2023, Humboldt Research Fellowship awarded by the Alexander von Humboldt Foundation (AvH)

Gros K, Analysis of surface sediments along the canyons in the region of the Rio Magdalena Delta in the Colombian Caribbean Sea, 2023, BSc Thesis, IfG, Mat Nat Faculty, Kiel University

Lopez AA, Quantifying fluxes of microplastics from the Magdalena River into the Caribbean Sea (in Spanish), 2024, BSc thesis, Universidad de Antioquia, Turbo, Colombia

Serna J, Andrés C, Rentería P, Armin D, Characterization of the phytoplankton community in the Guajira upwelling area, Colombian Caribbean, 2024, BSc theses, University of Antioquia

Machado Buelvas D, Geomorfología y procesos morfo sedimentarios recientes de los canones submarinos del Magdalena y La Aguja (sector central del Caribe colombiano), 2025, BsC thesis, Universidad de Norte, Barranquilla, Colombia

Cruise Report

MSM112: https://doi.org/10.48433/cr_msm112

MSM112/2

Sub-Tropical Atlantic Reference Data

Authors

University of Cologne, Institute of Zoology | Cologne, Germany

F. Nitsche, S. Schiwitz, J. Wagenhofer, H. Arndt, A. Scherwaß, J. Borchering, M. Hohlfeld, M. Sachs, J. Wagenhofer, D. Scepanski, J. Werner, B. Gräfe, A. Pyschny

Koninklijk Nederlands Meteorologisch Instituut | De Bilt, The Netherlands

P. Wang

Max Planck Institute for Chemistry | Mainz, Germany

S. Kinne, R. Adams

Hafen City University | Hamburg, Germany

G. D'Mello, G. Binda Souza

Institute of Geophysics Polish Academy of Sciences | Warsaw, Poland

B. Latos, M. Ciurylo

The MSM112/2 research cruise was dedicated towards the continued collection of reference data in the sub-tropics of the northern Atlantic along gradients of temperature and salinity. The activities had an atmospheric, an ocean-air exchange, a bathymetry and a biology component. Atmospheric activities focused on the collection of reference data for satellite remote sensing and global modeling, via sun-photometer samples, automatically recorded sky images and well-timed radiosonde releases.

The ocean-atmosphere investigations involved coordinated lower atmospheric profiles (with drones) in combination with upper ocean profiles (via CTD casts), with a focus on late afternoon times, when exchange processes at the ocean surface are expected to be at their maximum.

The time-series for atmospheric water during transit towards Africa displayed a general decline in an absolute sense (i. e. lower surface water concentrations) and in a relative sense (i. e. lower relative humidity). With fewer clouds and enhanced solar insolation values for the relative humidity often dropped below 60%, and relative humidity was (on average) lowest during the early afternoon. In contrast, during relatively few rain events (thus, times with significant cloud

cover) values near and in excess of 90% were reached. Tropical convection was associated with larger cloud-base contributions, more high-altitude clouds and significant inhomogeneity. Precipitation was also indicated by cloud bases below 500m. In contrast, (for sub-tropical climates) cloud cover remained low with lots of sunshine until stratocumulus decks near the Canary Islands were reached. The cloud cover daily cycles demonstrated that (in the subtropics in general) the total cloud cover was usually higher during the night and during the morning compared to usually less cloudy afternoons (also with the help of the solar insolation). Cloud-cover below 1km usually stayed below 3 octals except during nights and just before sunrise. The atmospheric aerosol loads were relatively weak during the entire voyage. Despite strong winds, which added extra sea salt aerosol from sea-spray, AOD values remained below values of 0.15, which is common for oceanic background conditions. The only major exception, which cannot be attributed to sporadic contamination by clouds or possible pollution, were on Nov 22nd a few miles off Aruba, likely from local pollution, and an extended case of larger AOD (of about 0.25) on Nov 25th near 18°N/51°W, likely from transported pollution. Predictions by an aerosol type forecast model the transport of pollution from western Africa to the ship location on that day. The aerosol particles are relatively large with Angstrom values usually below 0.6 and fine-mode fractions only around 0.6. This does not surprise with the relatively high surface windspeeds and associated white caps from breaking waves, which are expected to add extra relatively large sea-salt aerosol sizes. Only when AOD values are very low (compare to AOD data time-series), then (with lower larger size sea-salt concentrations) Angstrom and FMF display higher values. For aerosol effects on clouds, associations between fine-mode aerosol properties and low altitude water cloud properties are effective but there is a need for better observational constraints. Under the low background aerosol conditions (i. e. $AI < 0.1$) no significant aerosol impact on cloud cover was expected, although a few outliers point in the expected direction that with an increase to available sub-micrometer aerosol particles the low altitude cloud cover can increase. Vertical profiles from 15 radiosonde launches were directly compared for temperature, relative humidity and wind speed. Temperatures quickly decreased with altitude and reach their minimum at the tropopause only then to increased again by continuing into higher stratospheric altitude. Roughly there was a distinction between tropical Caribbean conditions (with cloud layers at all altitudes) and subtropical trade-wind conditions (with dry conditions and no cloud at mid-altitudes (ca 2–8km).

The first two validation profiles for the AEOLUS illustrated differences between tropical (Nov22) and sub-tropical conditions. There are more moderate windspeeds and high moisture through the entire troposphere in the tropics. In contrast, the sub-tropical profile displays much larger windspeeds in the upper troposphere (the jet-stream) and the atmosphere above the (marine) boundary layer is very dry (e. g. no clouds). Both profiles show the wind-direction changes from easterly winds near the surface turning clockwise to westerly (and especially

in the subtropics stronger) winds in the upper troposphere. In general, there was a good agreement between the AEOLUS retrieved winds and the quasi co-located radiosonde data.

UAV measurements show capability to identify changing environment. A comparison between profiles collected on Nov 24th and 26th showed small, but consistent differences in atmospheric stratification. These differences were visible in both temperature and humidity profiles. Changes to the vertical stratification and near surface temperature and salinity gradients are apparent. For example, ocean mixed layer temperature decreases towards Africa, where the water is also saltier. The layer of water temperature of ~15°C is much deeper in the east Atlantic, than in the west Atlantic. The salinity pattern is similar: layers of water with a higher PSU lay deeper in the east Atlantic than in the west Atlantic. CTD fluorescence – a primary indicator of the number of organisms – and a primary oxygen source – varied in relation to temperature and salinity but also greater depth of the maximum fluorescence layer is correlated to a higher insolation angle. On the other hand, peaks in fluorescence were the result of upwelling zones and colder currents (as seen in counter equatorial current). An abnormally deep warm layer of the ocean close to the Tropic of Capricorn can be attributed to the ocean currents.

The bathymetrical effort focused on the analysis of automatically recorded sea-floor data by echosounder and parasound and the data preparation for an eventual submission to the data-base of the SeaBed 2030 initiative. In addition, seamounts near the Canary Islands were surveyed. Depths here varied from -3775 m to -5435 m beneath the water surface. Some of the sea mounts measured a height of 1250 m. The survey helped in understanding the nature and structure of the group of sea mounts, which is of potential interest for future expeditions. Additionally, the survey shows the differences of quality with the GEBCO2022 grid.

The biology efforts focused on an examination of water samples from regular CTD casts with respect to the abundance and diversity of single celled eukaryotes (protist) in oceans and their distribution by air based on cultivation and DNA extraction. DNA from all samples and size classes was extracted and was processed in the home lab. Measurements of the DNA concentration show no significant decrease through the water column. Filters (10µm pore size), fixed in DESS and processed in the home lab, showed lower yield of DNA in general. First amplicons could be obtained by PCR using acanthoecid specific primer sets, including deep samples. PCR products were cleaned up and sequenced by Illumina MiSeq. First results from MiSeq for one station (including surface and DCM filter) with approx. 100,000 reads per sample, yielded about 35,000 reads clearly affiliated to acanthoecid choanoflagellates (p-distance less than 5%). Out of these 35,000 reads, about 1/3 show a 100% identity to reference sequences. 234 ASV could be assigned to choanoflagellates, mainly to the targeted

acanthoecids. The result regarding the spatial distribution shows a distinct separation between the Caribbean Sea and the North Atlantic Ocean, 76 ASV were found in the Caribbean Sea only and 117 were present only in the North Atlantic Ocean. The comparison of the vertical distribution showed that the Chlorophyll A Maximum layer harbors the highest number of choanoflagellate ASV, followed by the surface water. The lowest number was found in deeper water (500m), the number was decreasing with higher depths. The overlap is less than 10%, indicating a distinct vertical pattern for the distribution of choanoflagellates, likely caused by the presents of their prey, bacteria. As expected based on the results from previous cruises, rare species are barely cultivable. Mainly ubiquitous species like *Neobodo designis*, *Rhynchomonas nasuta*, *Hartaetosiga gracilis*, *Cafeteria* sp., several chrysomonads, dinoflagellates, ciliates and amoeba could be cultivated in clonal cultures, which has to be verified by sequencing the small sub unit (SSU) of the rRNA. At the end of the cruise we obtained around 40 strains and even more in the enriched samples which will be isolated by a micromanipulator back in Cologne, as this device is not suitable for use on board of a ship due to vibrations. In particular, the presence of the target organisms, coccolithophors and tintinnids, could be detected. The surface Sargassum samples showed a diverse protist community. We found representatives of many different phylogenetic groups of protists including bodonids, euglenids, choanoflagellates, ciliates, chrysomonads, bicosoecids, amoebae, cercozoans, ancyromonads, thaumatomonads and apusozoans.

Scientific Output

Data

Physical oceanography

Track:

<https://doi.org/10.1594/PANGAEA.957735>

<https://doi.org/10.1594/PANGAEA.957734>

CTD:

<https://doi.org/10.1594/PANGAEA.957417>

<https://doi.org/10.1594/PANGAEA.959025>

Bathymetry:

<https://doi.org/10.1594/PANGAEA.957210>

<https://doi.org/10.1594/PANGAEA.957207>

<https://doi.org/10.1594/PANGAEA.957205>

ADCP:

<https://doi.org/10.1594/PANGAEA.964709>

Cruise Report

MSM112/2:

https://doi.org/10.48433/cr_msm112_2

MSM113

First results of Cruise MSM113: Sediment wave generation in continental margins and the structure of the submerged mobile western flank of Cumbre Vieja Volcano, La Palma

Authors

Kiel University | Kiel, Germany

S. Krastel

Stockholm University | Stockholm, Sweden

C. Böttner

Leibniz Institute for Baltic Sea Research Warnemünde | Warnemünde, Germany

J. Geersen

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

P. Brandt, H. Huang

Monterey Bay Aquarium Research Institute | Moss Landing, US

R. Englert

Introduction

Two different proposals were realized in the frame of Cruise MSM113. The main objective of the cruise was to investigate sediment waves along the NW-African continental margin (Project WAVETEAM). Sediment waves are the dominant bedform on the ocean floor (Wynn & Stow, 2002; Rebesco et al., 2014). They are important for any seafloor infrastructure, such as telecommunication cables, as the flows passing over can be highly destructive (Lintern et al., 2016). Further, sediment waves play an important role in the stability of marine slopes (Laberg and Camerlenghi, 2008; Miramontes et al., 2018). However, the processes generating and maintaining sediment waves in open slope environments are often poorly constrained. The main objective of RV MARIA S. MERIAN Cruise MSM113 was an

interdisciplinary approach to study the processes that lead to the formation of large fields of sediment waves at the Northwest African continental margin.

The western unstable flank of the Cumbre Vieja volcano (La Palma) was mapped during the final five days of the cruise as part of a supplementary proposal (Project Sub:Palma). The new bathymetric data are analyzed to address hazards related to instability of this flank.

Sediment waves off NW-Africa

The R/V Maria S. Merian cruise MSM113 collected one of the most extensive, integrated datasets yet to capture processes at the water column – seafloor interface in muddy open slope sediment wave fields. This dataset includes oceanographic (CTD casts, moorings with ADCPs and turbidity sensors), hydroacoustic (multibeam echosounders, Parasound sub-bottom profiler), sedimentological (gravity and box cores) and seismic (2D multichannel) measurements from two study areas offshore NW Africa. Initial analysis focused on a sediment wave field at Cape Draa, offshore Morocco (Figure 1).

The sediment waves form prominent undulating topography on the seafloor between 600–1100 m water depth with wavelengths between 400–2000 m (average 1300 m), wave heights between 6–56 m (average 26 m), and local slope gradients up to 19° (Figure 1). The crests of the sediment waves are aligned perpendicular to the slope, in a northeast-southwest orientation. In seismic profiles the sediment wave package is ~ 365 m thick, indicating that the field has persisted for over 100 000s of years. The package has a stratified internal architecture with wavy semi-continuous – continuous stacked reflectors that are offset upslope. This suggests localized erosion and deposition over the sediment waves have resulted in upslope migration over this time (Figure 1C). Sediment cores from transects across sediment waves are composed of bioturbated sandy mud and muddy sand that form bi-gradational sequences 0.18–2.35 m thick. The composition of sediment particles is also mixed including silt – very fine sand terrigenous grains (quartz) and larger sand-sized marine biogenic grains (foraminifera, other calcareous material). Facies are consistent with lower sedimentation rates that are often associated with oceanographic processes such as bottom current or internal wave reworking (Normandeau et al., 2023). Differences in grain size are observed along transects with more sand (+5–12%), larger particles (100–300 µm), and sharper unit boundaries observed on the lee slope and trough of the sediment waves, indicating greater sediment transport and erosion at those locations.

The current regime observed by ADCPs on moorings positioned at a sediment wave trough and crest, are dominated by northeast slope-parallel currents for

most of the water column (>200 m above the seafloor; Figure 1C). At the seafloor, a greater across-slope velocity component is present with velocity fluctuations occurring at M2 tidal frequencies. The strongest flow velocities (~30 cm/s) are observed in the upslope direction at the sediment wave trough. These velocities can remobilize silt and fine sand based on calculated thresholds from grain size data between 20–40 cm/s (Miller et al., 1977). These locations also correspond to the highest seabed turbidity measurements on CTD casts and turbidity spikes in turbidity sensor and ADCP echo amplitude records. Thus, velocity and turbidity observations are aligned with sediment transport predictions based on sediment wave grain size transects and upslope migration patterns.

The integration of water column and seafloor observations provides a robust dataset to evaluate active processes shaping the continental slope. Flow directions over sediment waves are inconsistent with bottom currents which travel along-slope and turbidity currents which travel down-slope. Instead, fluctuating upslope and downslope flow with diurnal frequencies suggest relationships to local tidal flow or waves propagating with tidal frequencies. The water column is stratified over the depths where sediment waves occur which would allow for the propagation of internal waves. Velocity fluctuations are out-of-phase with the local tide supporting remote generation. Our observations suggest maintenance of the sediment wave field by internal tides and represent an important step to developing morphodynamical sediment wave models.

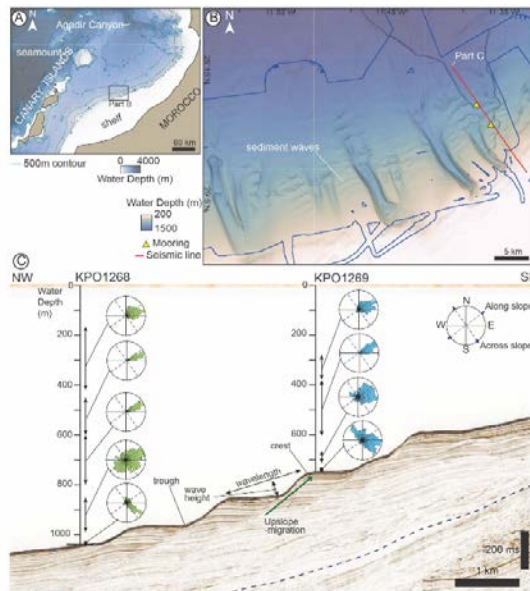


Figure 1: (A) Study area offshore Morocco. (B) Seafloor map of sediment wave field. Location in Part A. (C) Seismic profile across sediment waves. Rose diagrams show current flow direction for intervals of the water column covered by the ADCPs on the two moorings. Location in Part B.

Sediment transport through Agadir Canyon

Agadir canyon is adjacent to the large sediment wave fields (Figure 1A). Data collected in the head region of Agadir canyon during Cruise MSM113 contributed to the reconstruction of sediment gravity flows through Agadir Canyon. The Agadir Canyon initiated during the Middle Miocene on top of a preceding wide and shallow channel-levee-system. The Middle to Late Miocene saw the canyon continue eroding and narrowing into its present morphology. The evolution of the canyon was primarily driven by climate perturbations, sea level fluctuations and regional tectonic uplift of the Moroccan hinterland. These factors increased sandy sediment supply to the shelf edge, which promoted powerful erosive turbidity currents (Böttner et al., 2025). The erosive power of turbidity currents can dramatically increase their size, speed, and run-out distance. Hence, flow bulking is a first-order control on flow evolution and underpins predictive modeling approaches and geohazard assessments. We mapped the deposits and erosive destruction of a giant submarine gravity flow from source to sink in Agadir Canyon (Böttner et al., 2024). The small initial failure (~1.5 cubic kilometers) entrained over 100 times its starting volume, catastrophically evolving into a giant flow with a total volume of ~162 cubic kilometers and a run-out distance of ~2000 kilometers. Entrainment of mud was the critical fuel, which promoted run-away flow growth and extreme levels of erosion.

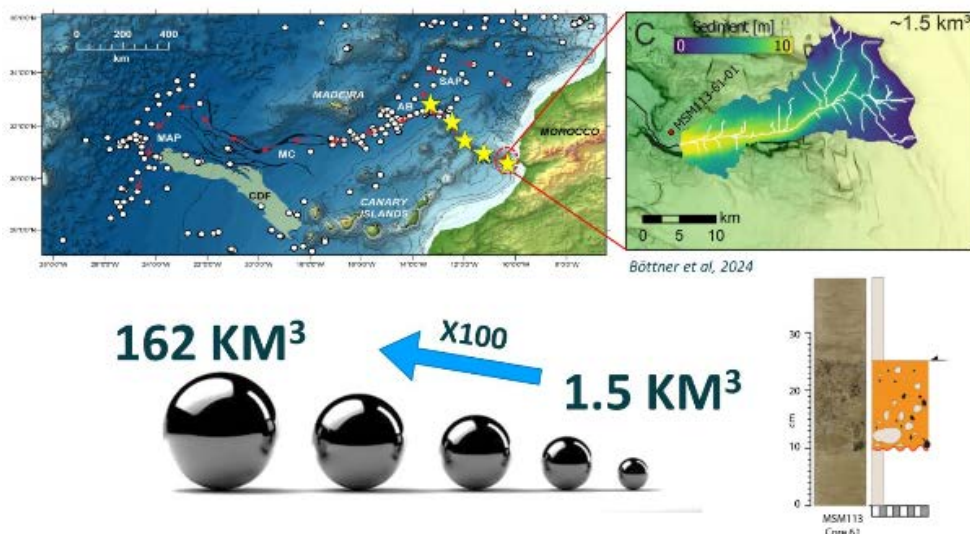


Figure 2: Reconstruction of the entrainment of a giant turbidity current in Agadir Canyon. The core in the lower right contributed to the reconstruction of the initial failure volume. The small initial failure (~1.5 cubic kilometers) entrained over 100 times its starting volume, catastrophically evolving into a giant flow with a total volume of ~162 cubic kilometers.

Geomorphological analysis of the unstable western flank of Cumbre Vieja Volcano (La Palma)

In 2021, the Cumbre Vieja volcanic complex on La Palma experienced its longest historical eruption (Carracedo et al., 2022). Although no geological evidence indicates a past sector collapse, ground deformation and field observations suggest progressive seaward movement of the western flank, consistent with the orientation of earlier island-scale failures. To evaluate the extent of this instability, we integrated geomorphological analyses of high-resolution topographic and newly acquired shipborne bathymetric data with shallow seismicity associated with the 2021 eruption (Rollwage et al., 2024). Results indicate that the Puerto Naos Ridge represents a tectonic boundary formed by uplift and transpressional deformation, separating a stable northern block from a mobile southern sector (Figure 3). The inferred unstable sector is consistent with the scale of deformation documented in prior geodetic studies and with flank collapses at comparable volcanic systems. Furthermore, we applied a semi-automated workflow for detecting morphological boundaries of unstable volcanic flanks from digital elevation data, validated through application to Mount Etna and Kilauea. This approach provides a transferable methodology for constraining potential failure zones and supports the design of future geophysical and geodetic monitoring strategies aimed at identifying precursory signals of flank collapse (Rollwage et al., 2024).

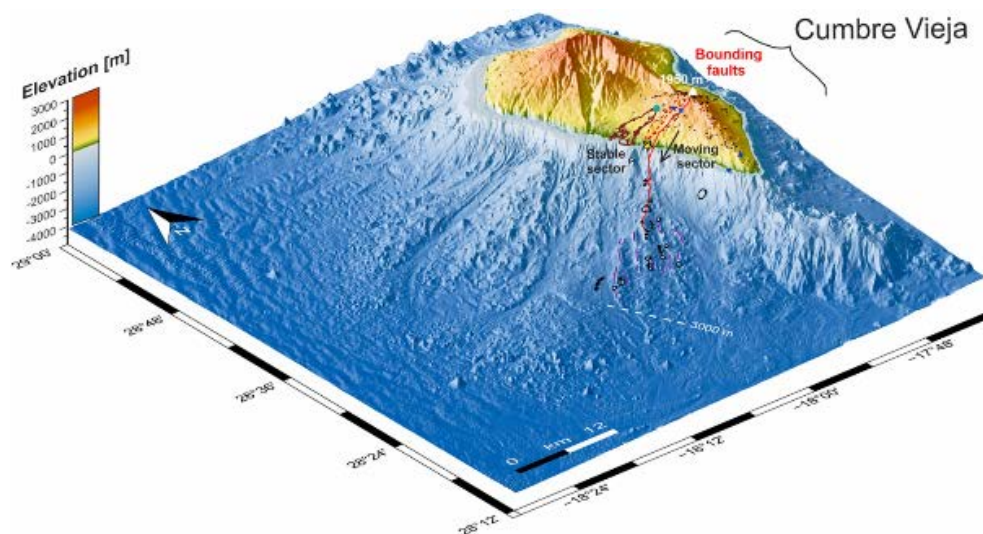


Figure 3: Perspective view of La Palma Island summarizing the main geomorphological interpretations of this study regarding the volcano-tectonic deformation of Cumbre Vieja's western flank (taken from Rollwage et al., 2024).

References

- Böttner C, Stevenson CJ, Englert R, Schöнке M, et al., Extreme erosion and bulking in a giant submarine gravity flow, *Science Advances* 2024, 10, eadp2584, doi: 10.1126/sciadv.adp2584.
- Böttner C, Stevenson CJ, Geersen J & Krastel S, The spatiotemporal evolution of a giant submarine canyon system – The Agadir Canyon, *Frontiers in Earth Science* 2025, 13, doi: 10.3389/feart.2025.1400289.
- Carracedo JC, Troll VR, Day JM, Geiger H, et al., The 2021 eruption of the Cumbre Vieja volcanic ridge on La Palma, Canary Islands, *Geol. Today* 2022, 38(3), doi: 10.1111/gto.12388.
- Laberg JS & Camerlenghi A, The significance of contourites for submarine slope stability, *Developments in Sedimentology* 2008, 60, doi: 10.1016/S0070-4571(08)10025-5.
- Lintern DG, Hill PR & Stacey C, Powerful unconfined turbidity current captured by cabled observatory on the Fraser River delta slope, British Columbia, Canada, *Sedimentology* 2016, 63(5), doi: 10.1111/sed.12262.
- Miller MC, McCave IN & Komar PD, Threshold of sediment motion under unidirectional currents, *Sedimentology* 1977, 24, doi: 10.1111/j.1365-3091.1977.tb00136.x.
- Miramontes E, Garziglia S, Sultan N, Jouet G, et al., Morphological control of slope instability in contourites: a geotechnical approach, *Landslides* 2018, 15(6), doi: 10.1007/s10346-018-0956-6.
- Normandeau A, Dafoe LT, Li MZ, Campbell DC, et al., Sedimentary record of bottom currents and internal tides in a modern highstand submarine canyon head, *Sedimentology* 2023, 71, doi: 10.1111/sed.13165.
- Rebesco M, Hernández-Molina FJ, Van Rooij D & Wåhlin A, Contourites and associated sediments controlled by deep-water circulation processes: state-of-the-art and future considerations, *Marine Geology* 2014, 352, doi: 10.1016/j.margeo.2014.03.011.
- Rollwage R, Sánchez-Guillamón O, Sippl C, León R, et al., Geomorphological evidence for volcano-tectonic deformation along the unstable western flank of Cumbre Vieja Volcano (La Palma), *Geomorphology* 2024, 465, doi: 10.1016/j.geomorph.2024.109401.

Wynn R & Stow D, Classification and characterization of deep-water sediment waves, *Marine Geology* 2002, 163, doi: 10.1016/S0025-3227(02)00547-9.

Scientific Output

List of Publications

Böttner C, Stevenson CJ, Englert R, Schönke M, et al., Extreme erosion and bulking in a giant submarine gravity flow, *Science Advances* 2024, 10, eadp2584, doi: 10.1126/sciadv.adp2584.

Böttner C, Stevenson CJ, Geersen J & Krastel S, The spatiotemporal evolution of a giant submarine canyon system – The Agadir Canyon, *Frontiers in Earth Science* 2025, 13, doi: 10.3389/feart.2025.1400289.

Rollwage R, Sánchez-Guillamón O, Sippl C, León R, et al., Geomorphological evidence for volcano-tectonic deformation along the unstable western flank of Cumbre Vieja Volcano (La Palma), *Geomorphology* 2024, 465, doi: 10.1016/j.geomorph.2024.109401.

List of conference presentations

2024 | **Making waves: Unraveling the processes generating sediment wave fields along the Northwest African margin** Conference on Seafloor Landforms, Processes, and Evolution, Lipari, Italy.

2024 | **Geomorphological evidence for volcano-tectonic deformation along the unstable western flank of Cumbre Vieja Volcano (La Palma)** Conference on Seafloor Landforms, Processes, and Evolution, Lipari, Italy.

2024 | **The evolution of the Agadir Canyon and its giant submarine gravity flow** Conference on Seafloor Landforms, Processes, and Evolution, Lipari, Italy.

2024 | **Deciphering the origin of sediment waves along the Northwest African margin through multidisciplinary analysis** EGU, Vienna, Austria.

2023 | **Agadir Canyon & Giant Gravity flows** GeoKolloquium, Aarhus, Denmark.

Data

ADCP:

<https://doi.pangaea.de/10.1594/PANGAEA.958196>

Thermosalinograph:

<https://doi.pangaea.de/10.1594/PANGAEA.957164>

Multibeam (EM712):

<https://doi.pangaea.de/10.1594/PANGAEA.965743>

Water column imaging (EM712):

<https://doi.pangaea.de/10.1594/PANGAEA.965744>

Multibeam (EM122):

<https://doi.pangaea.de/10.1594/PANGAEA.965107>

Water column imaging (EM122):

<https://doi.pangaea.de/10.1594/PANGAEA.966038>

Backscatter (EM122):

<https://doi.pangaea.de/10.1594/PANGAEA.973175>

Cruise Report

MSM113: https://doi.org/10.48433/cr_msm113

MSM114

Time series of benthic oxygen and carbon cycling subjected to enhanced export production driven by mesoscale eddies off West Africa

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

S. Sommer, A.W. Dale

Introduction & objectives

The research cruise MSM114 with the RV MARIA S. MERIAN was carried out within the framework of the projects REEBUS “Role of Eddies in the Carbon Pump of Eastern Boundary Upwelling Systems” and MOSES funded by the Helmholtz Society and the German Ministry for Education and Research. Specific aim of the cruise was to resolve changes of the organic carbon degradation in deep-sea sediments in relation to the passage of productive eddies at the sea surface. Hence, to record a time series of benthic oxygen consumption affected by the elevated deposition of particulate organic carbon during the passage of an eddy, the novel Deep-Sea Rover (DSR) Panta Rhei and the stationary lander DOS (Deep Sea Observation System) have been placed at the deep-sea floor at the site E2 during the RV METEOR Expedition M182 (May/July 2022). E2 is located ca. 160 km northeast of the Cape Verdian island Sal in a water depth of 3300 m.

The short research cruise MSM114 comprising 2 working days served for the recovery of the DSR and the DOS. This cruise concludes the measurement campaigns M156 (July/Aug. 2019), M160 (Nov./Dec. 2019), M182 (May/July 2022), which were conducted within REEBUS and MOSES. Additionally, meteorologists from the Max-Planck-Institut für Meteorologie (S. Kinne) and the Koninklijk Nederlands Meteorologisch Instituut, De Bilt (Piet Stammes, KNMI) participated on the cruise to perform underway shipboard meteorological measurements. These measurements encompass meteorological data, cloud observations, and the deployment of radiosondes. They were described in detail in the cruise report (Sommer et al. 2023).

Scientific background

Eddies are key features of the ocean and responsible for many of its large-scale properties. Eddy generation is favored by the interaction of large-scale currents with the bottom topography, islands or headlands, by barotropic or baroclinic instability of currents and fronts, or by atmospheric forcing (e. g. Thomsen et al 2016). During eddy generation, coastal waters from the upwelling region are trapped in the core of the eddy and subsequently transported offshore. Thus, they play an important role in lateral mixing and in the transport of physical and biogeochemical properties. Thereby, they modulate biological productivity and biogeochemistry. It has been shown that three different types of eddies (cyclonic, anticyclonic, anticyclonic mode water) have different, far-reaching effects. This includes strong effects on biological productivity and biogeochemical processes (e. g. Stramma et al., 2013). In the Canary Current System, effects of eddies on the subsurface oxygen concentration leads to severe hypoxia and causing redox-dependent biogeochemical and biological responses (e. g. Fiedler et al. 2016, Hauss et al. 2016, Löscher et al. 2016). Furthermore, eddies may be hotspots of prokaryotic activity and different community structures (e. g. Hauss et al. 2016) and are important in the vertical export of organic matter (Fischer et al. 2021, 2016a) and its transport to deep-sea sediments, thereby directly connecting surface ocean dynamics with the deep ocean (Zhang et al. 2014).

Most of the biomass produced in coastal upwelling cells is advected horizontally towards the open ocean by filaments and mesoscale eddies (Fischer et al. 2009, 2016b). The efficient transfer of phytoplankton biomass to the deep-sea floor is further supported by dust storms that may fertilize the ocean with iron and phosphate, creating diatom blooms, and provide ballast material for the rapid transfer of organic matter into the deep ocean (Fischer et al. 2016b). In situ benthic carbon turnover measurements in the deep-sea are still rare (Jørgensen et al. 2022). Therefore, it is not known what fraction of the phytoplankton biomass is removed from the water column and sequestered in the benthos and how this downward flux is mediated by eddies.

Methods & Results

The main working area of the cruise MSM114 was the site E2 at 18° N, Figures 1 and 2. The station E2 belongs to a series of sampling sites (E1 to E5) along a zonal section at 18° N covering different water depths and distances from coast of Cape Verde and Mauritania. These stations were intensely sampled during the previous cruises M156 and M182. E2 represents a deep-sea benthic station in 3300 m water depth. The sediment is soft consolidated mud with a smooth flat surface without any major obstacles extending over the sediment surface ideal for the operation of the DSR. The zonal section along 18° N is located within the passage of mesoscale

eddies that are generated along the West African coast and propagate with an average velocity about 3.0 km d⁻¹ westwards into the open ocean (Schütte et al. 2016).

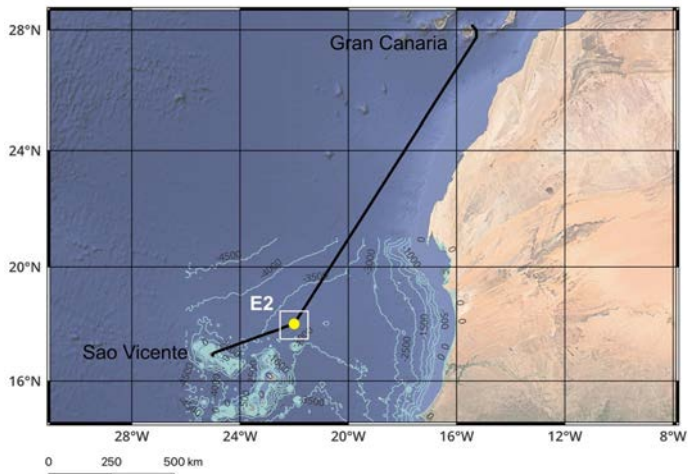


Figure 1: Working area E2 located ca. 160 km northeast of the Cape Verdian island Sal.

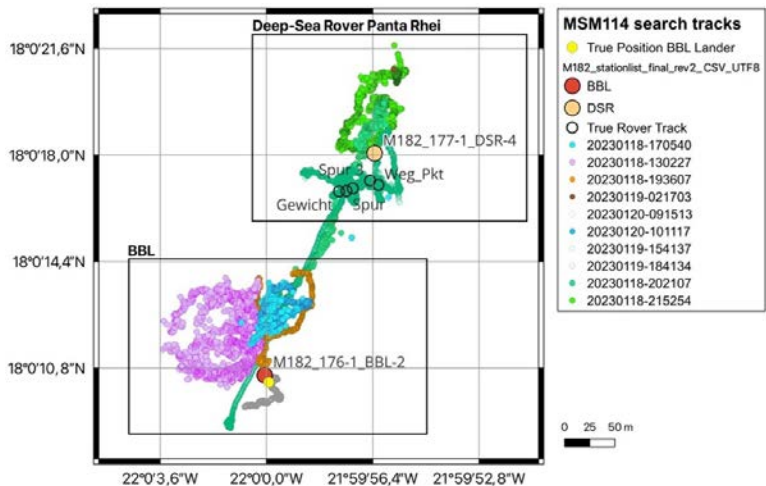


Figure 2: Details of the ship track in the working area E2 for the search of the DOS Lander (BBL) and during the survey to follow the track left by Deep-Sea Rover (DSR) Panta Rhei at the seafloor.

The working program comprised 2 working days for the recovery of the DOS Lander and the DSR. In order to measure the variability of the total oxygen uptake (TOU) in relation to the passage of productive eddies at the sea surface the DSR was deployed for the first time in the deep-sea. The DSR represents a six-wheeled

vehicle (weight in air 1200 kg, 80 kg in water, dimensions 3 x 2 x 1.7 m (L, W, H)), which was specifically designed to carry out repeated benthic oxygen flux measurements inside two benthic chambers at the front of the vehicle for prolonged time periods of up to one year, Figure 3. Additionally, the Rover carries three camera systems, two of which are forward looking, the other one takes photographs of the seafloor behind the vehicle.

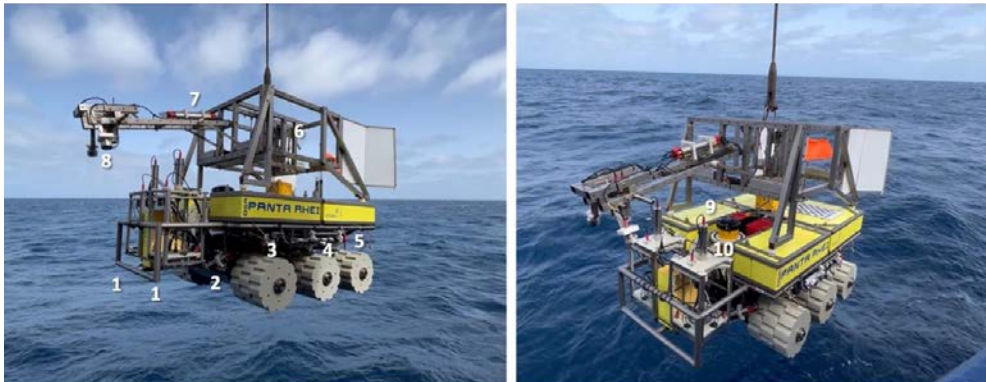


Figure 3: Deployment of the DSR Panta Rhei at the E2 working area for the long-term measurement of TOU. (1) two chambers for benthic flux measurements, (2) one of three cameras, (3) Wetlab turbidity sensor, (4) Seabird CTD SBE 19plus (5) rear camera, (6) launching unit from which the Rover is uncoupled using an electric releaser when the seafloor is reached (7) telemetry for signal and energy transfer (8) camera and lights of the launching unit, (9) profiling current meter (ADCP), (10) pump for volume determination. Photos Gabriel Nolte. Image also published in the RV Meteor cruise report M182.

At the 19 January 2023 about six months after its deployment we successfully recovered the DSR from deep-sea floor. During the entire time period the DSR successfully performed seafloor imaging. Using the backward camera images freshly deposited particles could be identified on the sediment surface. Counts of these particles indicated an onset of increased particle deposition at the beginning of October 2022.

TOUs were measured until the middle of August 2022 in the left chamber and until beginning of October 2022 in the right chamber. Afterwards there was a failure of the retrieval and insertion mechanism of the flux chambers. Unfortunately, TOU measurements did not cover the time period of enhanced particle deposition. Nevertheless, over the time period between 04.07.–01.10.2022 a total of 76 TOUs were successfully measured and a short time series of deep-sea benthic oxygen consumption at E2 has been successfully recorded. By means of conventional lander- based measurements this cannot be achieved. The mean TOU was $0.66 \pm 0.07 \text{ mmol m}^{-2} \text{ d}^{-1}$. Minimum and maximum oxygen consumption was 0.42 and $0.98 \text{ mmol m}^{-2} \text{ d}^{-1}$ respectively. In comparison, according to the empirical equation globally relating TOU the water depth (Jørgensen et al. 2022) the calculated oxygen uptake was higher and amounts to $0.9 \text{ mmol m}^{-2} \text{ d}^{-1}$. As also implied

by seafloor imaging and particle counting the TOU measured during the DSR deployment was measured under conditions of low allochthonous carbon input.

The repeated TOU measurements performed by the DSR strongly contribute to obtain a better understanding of carbon turnover in the deep-sea and its coupling to the surface ocean export production. The results are currently interpreted in the context of previous TOU measurements made along the entire depth transect at 18°N from the coast of Mauritania to the Cape Verde islands during the RV Meteor cruises M107 M156, M182, and the Maria S. Merian cruise MSM17/4 (Dale et al. 2014).

Acknowledgements

This cruise was approved and funded by the “Gutachterpanel Forschungsschiffe” of the German Research Foundation under license no. GPF 21-1_009, MOSES Eddy Study IV. Further support was kindly provided by BMBF for the REEBUS project “Role of Eddies in the Carbon Pump of Eastern Boundary Upwelling Systems” (03F0815D). and the MOSES project “Modular Observation Solutions for Earth Systems”.

References

- Dale AW, Sommer S, Ryabenko E, Noffke A, Bohlen L, et al., Benthic nitrogen fluxes and fractionation of nitrate in the Mauritanian oxygen minimum zone (Eastern Tropical North Atlantic), *Geochimica Cosmochimica Acta* 2014, 134, doi.org/10.1016/j.gca.2014.02.026.
- Fiedler B, Grundle D, Schütte F, Karstensen J, et al., Oxygen utilization and downward carbon flux in an oxygen-depleted eddy in the Eastern Tropical North Atlantic, *Biogeosciences* 2016, 13, doi.org/10.5194/bg-13-5633-2016, 2016.
- Fischer G, Romero OE, Karstensen J, Baumann, K-H, et al., Seasonal flux patterns and carbon transport from low-oxygen eddies at the Cape Verde Ocean Observatory: lessons learned from a time series sediment trap study (2009-2016), *Biogeosciences* 2021, 18, doi.org/10.5194/bg-18-6479-2021.
- Fischer G, Karstensen J, Romero O, Baumann KH, et al., Bathypelagic particle flux signatures from a suboxic eddy in the oligotrophic tropical North Atlantic: production, sedimentation and preservation. *Biogeosciences* 2016a, 13, doi.org/10.5194/bg-13-3203-2016.

Fischer G, Romero O, Merkel U, Donner B, et al., Deep ocean mass fluxes in the coastal upwelling off Mauritania from 1988 to 2012: variability on seasonal to decadal timescales, *Biogeosciences* 2016b, 13, doi.org/10.5194/bg-13-3071-2016.

Fischer G, Reuter C, Karakas G, Nowald N, et al., Offshore advection of particles within the Cape Blanc filament, Mauritania: Results from observational and modelling studies, *Prog. Oceanogr.* 2009, 83, doi: 10.1016/j.pocean.2009.07.023.

Hauss H, Christiansen S, Schütte F, Kiko R, et al., Dead zone or oasis in the open ocean? Zooplankton distribution and migration in low- oxygen modewater eddies, *Biogeosciences* 2016, 13, doi.org/10.5194/bg-13-1977-2016, 2016.

Löscher CR, Fischer MA, Neulinger SC, Fiedler B, et al., Hidden biosphere in an oxygen-deficient Atlantic open-ocean eddy: future implications of ocean deoxygenation on primary production in the eastern tropical North Atlantic, *Biogeosciences* 2015, 12, doi.org/10.5194/bg-12-7467-2015, 2015.

Schütte F, Brandt P & Karstensen J, Occurrence and characteristics of mesoscale eddies in the tropical northeastern Atlantic Ocean, *Ocean Sci.* 2016, 12, doi.org/10.5194/os-12-663-2016.

Sommer S, Dale AW, Glemser B, Kinne S, et al., Time series of benthic oxygen and carbon cycling subjected to enhanced export production driven by mesoscale eddies off West Africa (MOSES Eddy Study IV), Cruise No. MSM114, 15.01.–21.01.2023, Las Palmas (Spain) – Mindelo (Cape Verde), doi:10.48433/cr_msm114.

Stramma L, Bange HW, Czeschel R, Lorenzo, et al., On the role of mesoscale eddies for the biological productivity and biogeochemistry in the eastern tropical Pacific Ocean off Peru, *Biogeosciences* 2013, doi.org/10.5194/bg-10-7293-2013, 2013.

Thomsen S, Kanzow T, Krahmann G & Greatbatch RJ, The formation of a subsurface anticyclonic eddy in the Peru-Chile Undercurrent and its impact on the near-coastal salinity, oxygen, and nutrient distributions, *J. Geophys. Res. Oceans* 2016, 121, doi.org/10.1002/2015JC010878.

Zhang Z, Wang W & Qui B, Oceanic mass transport by mesoscale eddies, *Science* 2014, 345, doi: 10.1126/science.1252418.

Scientific Output

List of conference presentations

2025 | **Benthic biogeochemistry from the Mauritanian margin to the deep sea.** HWK Study Group on Deep-Sea Ecosystems offshore W African, Hanse Wissenschaftskolleg, Delmenhorst, Germany.

Data

Rover data and images:
GEOMAR repository, to be published in July 2026

Meteorological data:
S. Kinne (formerly MPI-M, Hamburg), Piet Stammes (KNMI)

Cruise Report

MSM114: https://doi.org/10.48433/cr_msm114

MSM114/2

Atlantic References and Convection

Authors

University of Cologne, Institute of Zoology | Cologne, Germany

F. Nitsche, J. Wagenhofer, D. Paul, L. Hayo

Koninklijk Nederlands Meteorologisch Instituut | De Bilt, The Netherlands

P. Stammes, O. Tuinder

Max Planck Institute for Meteorology | Hamburg, Germany

J. Windmiller, L. Köhler, S. Kinne, M. Attias-Kinne

Hafen City University | Hamburg, Germany

B. Lobo, T. Nischik

Institute of Geophysics Polish Academy of Sciences | Warsaw, Poland

B. Latos, D. Kepski, M. Brennek

The MSM114/2 research cruise was dedicated towards the continued collection of reference data along a latitudinal cross-section from 16 N to 45 S with a special focus on tropical convection in the Inter-Tropical Convergence Zone (ITCZ) near the Atlantic equator. The activities had an atmospheric, an ocean-air exchange, a bathymetry and a biology component. Atmospheric activities focused on the collection of reference data for satellite remote sensing and global modeling, via samples by sun-photometers, a size-segregated aerosol mass sampler, recorded sky images, a cloud-base altitude detector, a microwave radiometer to record atmospheric water vapor and liquid water and well-timed radiosonde releases. On three equator crossing legs through the tropical convection more than 80 radiosondes were released to capture the atmospheric state. Wind data profiles from some of these radiosondes plus data from a few extra radiosonde launches were also used to evaluate satellite-based wind data estimate during rare overpasses. The ocean-atmosphere investigations involved coordinated lower atmospheric profiles (with drones) in combination with upper ocean profiles (via CTD casts) with a preference for late afternoon times, when exchange processes at the ocean surface are expected to be at their maximum. One of the main objectives of ARC was to obtain vertically resolved cross sections of the Intertropical Convergence Zone (ITCZ). To this end, we crossed the ITCZ three times in the meridional direction. Within ITCZ, there is much more humidity at all levels. Here, a temperature inversion, together

with a sudden increase in humidity to nearly 100% was observed at ~300m ASL. We present the atmospheric and oceanographic measurements collected during ARC in a standardised way to facilitate working with data from different instruments and to make the data easily accessible. This approach is not limited to ARC but could serve as a prototype for future (and past) ship campaigns. We present data from the integrated ship sensors (DSHIP); a humidity and temperature profiler (HATPRO); a ceilometer; aerosol instruments (DustTrak, Microtops, and Calitoo); radiosondes; uncrewed aircraft vehicles (UAVs); and conductivity, temperature, and depth (CTD) profiles of the upper ocean. We distinguish between temporal continuous data (DSHIP, HATPRO, Ceilometer, and DustTrak) from point measurements (radiosondes, UAVs, CTDs, Calitoo, and Microtops). To illustrate the data sets provided, we present examples of measurements taken during the three crossings of the ITCZ and during a storm in the Roaring Forties in the South Atlantic at the end of the campaign. Within the ITCZ, the integrated water vapor usually rises above ca. 50 kg/m². The third crossing of the inner ITCZ showed a lower relative humidity for higher altitudes compared to its edges. Compared to this, the first two crossings exhibited much higher relative humidity especially in higher altitudes. Wind speeds usually stayed below 15m/s, and were stronger in the tropics near convection. In contrast, in-between the northern and southern convection bands of the ITCZ, there were often regions of low wind-speeds (doldrums), as during the third tropical crossing, when surface water was only moved by swell. The highest solar irradiances were about 1125 W/m² at cloud-free conditions, with a solar constant of 1360 W/m² at the Top Of the Atmosphere (TOA) this translates into a solar broadband atmospheric transmission of more than 80%, with major losses attributed to trace-gases (i. e. water vapor and ozone) and with minor losses due to molecular scattering and due to low aerosol loads on that day. Cloud cover during the cruise was generally low and then mainly caused by lower altitude clouds. Periods of higher cloud cover and higher inhomogeneity at higher altitudes occurred with rain bands in the ITCZ and later with synoptical systems and storms at southern mid-latitudes. The associations between aerosol properties of AOD or Angstrom and the surface wind speed are not very clear also as many observed aerosol situations include transported aerosol with little interactions with the surface winds. When winds near the surface become so strong that sea-spray develops, then an increasing number of larger super-micron sea-salt aerosols above the water is expected to increase the aerosol load (AOD) and with larger AOD contributions then from larger sizes for lower Angstrom parameter values. Interesting even though at wind-speeds as large as 13m/s background AOD values are observed, unlike on other cruises where an increase of the lowest AOD and associated decreases of Angstrom parameter occurs already at wind-speeds in excess of 8 m/s. A peak in the Angstrom parameter on Feb 2nd, indicating that these were small particles, originating from biomass burning in Africa. In contrast, the peak in AOD around Jan 26th had a small Angstrom parameter, indicating large desert dust particles. The Dusttrak measured the coarse dust aerosol on Feb 2nd, but not the fine smoke aerosol. On the other hand, the smoke aerosol dominated the AOD measurements on that day, which can be seen from the large Angstrom exponent.

Based on the chlorophyll content, waters were nutrient-poor during the entire cruise from the Cape Verde Island to southern mid-latitudes, especially for the crossing of the southern sub-tropics (west of 20°W). Only beyond 45°S, when colder waters were reached (not shown here) chlorophyll level sharply increased.

The bathymetrical effort focused on a preparation of automatically recorded sea-floor data via (multibeam) echosounder and parasound instruments for the data-base of the SeaBed 2030 initiative. In addition, seamounts in the Southern Atlantic were surveyed.

During 28 days of survey, a track length of 6431 nm (11.576 km) was surveyed covering an area of 686,451 km². The raw data volume of the EM122 including water column data amounts to 46 GB with 1204 separate files for *.all and 518 *.wcd data type. The water depths ranged between a minimum of -300 m in the continental shelf of Cap Verde and a maximum of -7100 m in the mid and south Atlantic Ocean.

A Multibeam survey was done to map a seamount which is not yet on the NOAA grid or GEBCO grid. Depths here varied from 1600 m to 4800 m beneath the water surface, the height of the seamount is 2700 m and the survey helped in understanding the nature and structure of the seamount. The volcanic rise can be found at 34°5'22" S, 32°53'49" W.

The biology efforts focused on an examination of vertical and horizontal water samples from regular CTD casts for DNA extraction to study unicellular eukaryotes. A targeted PCR was performed to select acanthoecid choanoflagellates. Measurements of the DNA concentration show no significant decrease through the water column. Filters (10µm pore size), fixed in DESS and processed in the home lab, showed lower yield of DNA in general. First amplicons could be obtained by PCR using acanthoecid specific primer sets, including deep samples. PCR products were cleaned up and sequenced by Illumina MiSeq. First results from MiSeq for one station (including surface and DCM filter) with approx. 100,000 reads per sample, yielded about 35,000 reads clearly affiliated to acanthoecid choanoflagellates (p-distance less than 5%). Results show a distinct vertical and horizontal distribution pattern. As expected based on the results from previous cruises, rare species are barely cultivable. Mainly ubiquitous species like *Neobodo designis*, *Rhynchomonas nasuta*, *Hartaetosiga gracilis*, *Cafeteria* sp., several chrysomonads, dinoflagellates, ciliates and amoeba could be cultivated in clonal cultures, which has to be verified by sequencing the small sub unit (SSU) of the rRNA. At the end of the cruise we obtained around 40 strains and even more in the enriched samples which will be isolated by a micromanipulator back in Cologne, as this device is not suitable for use on board of a ship due to vibrations. In particular, the presence of the target organisms, coccolithophors and tintinnids, could be detected.

Scientific Output

List of Publications

Köhler L, Windmiller J, Baranowski D, Brennek M, Ciuryło M, Hayo L, Kępski D, Kinne S, Latos B, Lobo B, Marke T, Nischik T, Paul D, Stammes P, Szkop A & Tuinder O, Calm ocean, stormy sea: atmospheric and oceanographic observations of the Atlantic during the Atlantic References and Convection (ARC) ship campaign, Earth Syst. Sci. Data 2025, 17, 633–659, <https://doi.org/10.5194/essd-17-633-2025>.

Data

Physical oceanography

Track:

<https://doi.org/10.1594/PANGAEA.962171>

<https://doi.org/10.1594/PANGAEA.962170>

CTD:

<https://doi.org/10.1594/PANGAEA.966643>

<https://doi.org/10.1594/PANGAEA.960134>

<https://doi.org/10.1594/PANGAEA.957927>

<https://doi.org/10.1594/PANGAEA.971941>

<https://doi.org/10.1594/PANGAEA.966616>

Bathymetry:

<https://doi.org/10.1594/PANGAEA.957925>

<https://doi.org/10.1594/PANGAEA.957926>

ADCP:

<https://doi.org/10.1594/PANGAEA.957638>

<https://doi.org/10.1594/PANGAEA.957639>

Calitoo:

<https://doi.org/10.1594/PANGAEA.966644>

DustTrack:

<https://doi.org/10.1594/PANGAEA.966621>

Ceilometer:

<https://doi.org/10.1594/PANGAEA.966619>

<https://doi.org/10.1594/PANGAEA.966620>

Cloud camera:

<https://doi.org/10.1594/PANGAEA.966662>

DShip:

<https://doi.org/10.1594/PANGAEA.966617>

HATPRO:

<https://doi.org/10.1594/PANGAEA.966618>

Micotops:

<https://doi.org/10.1594/PANGAEA.966645>

Radiosonde:

<https://doi.org/10.1594/PANGAEA.966640>

<https://doi.org/10.1594/PANGAEA.966638>

<https://doi.org/10.1594/PANGAEA.966637>

UAV:

<https://doi.org/10.1594/PANGAEA.966641>

<https://doi.org/10.1594/PANGAEA.966642>

Cruise Report

MSM114/2: https://doi.org/10.48433/cr_msm114_2

MSM115

Scientific Results of MSM115

Authors

University of Hamburg | Hamburg, Germany

H. Herr

University of Gdańsk | Gdynia, Poland

A. Panasiuk

Tethys Research Institute | Milan, Italy

S. Panigada

Fin whales (*Balaenoptera physalus*) of the Southern Hemisphere were severely depleted by 20th century commercial whaling and their population status is currently unknown. However, recent observations of large fin whale feeding aggregations at Southern Ocean foraging grounds represent a visible sign of ongoing population recovery. Yet, the mechanisms driving their occurrence have not yet been studied, knowledge on the feeding ecology is limited and the migratory origin of fin whales at these grounds remains unknown.

MSM115 'FINWAP' was a dedicated fin whale research cruise to the feeding grounds off the Antarctic Peninsula. The main objectives were to: (a) estimate fin whale abundance, (b) describe migratory routes and destinations, (c) investigate predator-prey relationships, and (d) identify drivers of fin whale feeding aggregations.

We conducted a visual whale survey concurrently to a macro-zooplankton net-trawl and an oceanographic survey, at the same temporal and spatial scale, along a pre-defined survey grid. Furthermore, we equipped fin whales with satellite transmitters to track their movements and we collected skin biopsy and fecal samples for dietary analyses. Drone video footage was also collected for behavioural analyses.

Fin whale abundance was estimated at $6,561 \pm 1,802$ animals (95% CI: 3,816–11,278; CV: 27.47 %) across three feeding grounds (corresponding to the areas around the South Shetland Islands, Elephant Island and the South Orkney Islands) (Figure 1).

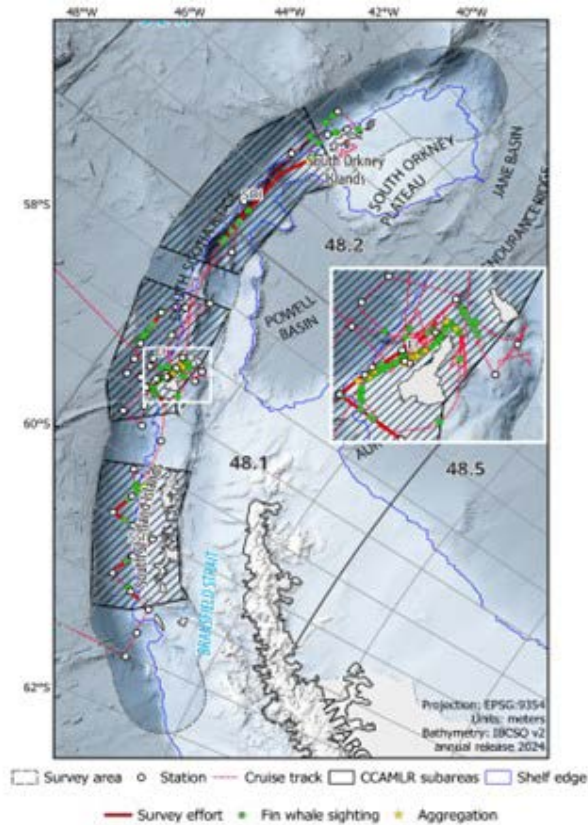


Figure 1: Survey area of MSM115 with three strata corresponding to three fin whale feeding grounds (SSI = South Shetland Islands, EI = Elephant Island, SOI = South Orkney Islands). Macrozooplankton and oceanographic sampling were conducted at all stations shown, visual survey effort is indicated as bold red line, with sightings of fin whales and fin whale aggregations indicated. From: Herr et al. *under review*.

Based on the data from the concurrent whale krill and oceanographic surveys, we identified hydrological signatures linked to shelf-incising submarine canyons as the primary drivers of fin whale feeding aggregations. Our results suggest that watermass- mixing promotes krill aggregation across age classes (Panasiuk et al. *submitted*), providing concentrated prey fields which fin whales exploit. Tracking data from the deployed satellite transmitters further revealed that fin whales align their movements with canyon structures, underscoring canyon-driven hydrodynamics as key habitat-structuring features (Herr et al., *under review*).

Nine satellite transmitters were successfully deployed on fin whales during MSM115. Tracking data showed a strong site fidelity of fin whales to their feeding grounds and a high degree of area restricted search behaviour (ARS), indicative of intense feeding activity. Also, direct transits between different island feeding grounds were evident from the tracking data (Panigada et al. *under review*).

Together, the results of MSM115 identify critical fin whale feeding habitat to be limited to a narrow band along the shelf edge – an area that is also the main target of the commercial krill fishery (CCAMLR 2025). A comparison of the distribution patterns of fin whales and krill fishery effort using a structural similarity index revealed significant fine-scale overlap on the feeding grounds (Daume 2024). This spatial overlap raises concerns of competition and potential population-level impacts, particularly as recovering fin whale populations increasingly depend on these limited foraging habitats.

Our cruise results confirm the significance and the ecological importance of Elephant Island, highlighting the need for targeted conservation measures. Unique oceanographic conditions owing to the bottom topography and the water masses which are influenced by the Antarctic Circumpolar Current support this area as a crucial recruitment area for Antarctic krill (*Euphausia superba*) and critical foraging ground for top predators, making Elephant Island and its surrounding waters a prime candidate for protection (Panasiuk et al. submitted; Panasiuk et al. under review).

Analyses of drone video data provided novel insights into feeding behaviour and found first evidence for group foraging and cooperative feeding strategies in Southern Hemisphere fin whales (Rychwalski 2024, Rychwalski & Herr, *submitted*).

In addition to the finalized analyses, cruise MSM115 has generated valuable resources for ongoing and future research. Biopsy samples and photo-identification images have been collected and are currently analysed as part of two PhD theses.

Altogether, data collected during MSM115 greatly contributed to advancing our understanding of the population status and ecology of Southern Hemisphere fin whales, their habitat use and feeding behaviour, and provide robust and sound knowledge for the conservation and management of this recovering population.

References

- CCAMLR, Fishery Report 2024: *Euphausia superba* in Area 48, CCAMLR Secretariat 2025, Hobart, Tasmania, Australia,
https://fishdocs.ccamlr.org/FishRep_48_KRI_2024.pdf.
- Herr H, Viquerat S, Vortkamp M & Panasiuk A, Canyon-effects structure fin whale feeding aggregations at Southern Ocean feeding grounds, *Ecosphere*, under review.

Daume HV, Spatio-temporal association and overlap of fin whale distribution and krill fisheries at the Western Antarctic Peninsula, Master Thesis 2024, University of Hamburg, Hamburg, Germany.

Panasiuk A, Viquerat S, Vortkamp M, Hoszek-Mandera K & Herr H, Abiotic factors promoting euphausiids diverse community structure over the western shelf of the South Shetland and South Orkney islands (Western Antarctic) with a special focus on the Antarctic krill *Euphausia superba*, Ecology, submitted.

Panasiuk A, Herr, H, Hoszek-Mandera & Krüger L, Elephant Island (Western Maritime Antarctic Peninsula) as an unique oceanographic area in terms of zooplankton communities and top predator abundances – case study in the context of planning MPAs, Aquatic Conservation, under review.

Panigada S, Panigada V, Hickmott L, Kennedy A & Herr H, Insights into fin whale movements and foraging behaviour around Elephant Island, Antarctica, Journal of Cetacean Research and Management, under review.

Scientific Output

List of Publications

Herr H, Viquerat S, Vortkamp M & Panasiuk A, Canyon-effects structure fin whale feeding aggregations at Southern Ocean feeding grounds, Ecosphere, *under review*.

Panasiuk A, Viquerat S, Vortkamp M, Hoszek-Mandera K & Herr H, Abiotic factors promoting euphausiids diverse community structure over the western shelf of the South Shetland and South Orkney islands (Western Antarctic) with a special focus on the Antarctic krill *Euphausia superba*, Ecology, *submitted*.

Panasiuk A, Herr, H, Hoszek-Mandera & Krüger L, Elephant Island (Western Maritime Antarctic Peninsula) as an unique oceanographic area in terms of zooplankton communities and top predator abundances – case study in the context of planning MPAs, Aquatic Conservation, *under review*.

Panigada S, Panigada V, Hickmott L, Kennedy A & Herr H, Insights into fin whale movements and foraging behaviour around Elephant Island, Antarctica, Journal of Cetacean Research and Management, *under review*.

Rychwalski AN, Cooperative feeding strategies and lateralised lunge feeding behaviour of Southern Hemisphere fin whales within large feeding aggregations at the Western Antarctic Peninsula, Master Thesis 2024, University of Hamburg, Hamburg Germany.

Daume HV, Spatio-temporal association and overlap of fin whale distribution and krill fisheries at the Western Antarctic Peninsula, Master Thesis 2024, University of Hamburg, Hamburg, Germany.

List of conference presentations

2025 | **Spatio-temporal association and overlap of fin whale distribution and krill fisheries at the Western Antarctic Peninsula** Annual Conference of the European Cetacean Society, Ponta Delgada, Portugal.

2025 | **Cooperative feeding strategies of Southern Hemisphere fin whales** Annual Conference of the European Cetacean Society, Ponta Delgada, Portugal.

2025 | **Deep Learning Approach for automated photo identification using vertical drone imagery of fin whales** Annual Conference of the European Cetacean Society, Ponta Delgada, Portugal.

2024 | **Recovery status and ecology of fin whales at the Western Antarctic Peninsula** International Polar Conference, Rauris, Austria.

2024 | **Insights into fin whale movements and foraging behaviour around Elephant Island, Antarctica** Annual Conference of the European Cetacean Society, Catania, Italy.

Data

Mastertrack:

<https://doi.org/10.1594/PANGAEA.962660>

Visual Whale Survey:

<https://doi.pangaea.de/10.1594/PANGAEA.984312>

Opportunistic whale observations:

<https://doi.pangaea.de/10.1594/PANGAEA.984262>

Macrozooplankton survey (trawl):

<https://doi.pangaea.de/10.1594/PANGAEA.984307>

Krill and salp length distribution:

<https://doi.pangaea.de/10.1594/PANGAEA.984305>

Oceanographic survey (CTD):

<https://doi.pangaea.de/10.1594/PANGAEA.984226>

Cruise Report

MSM115: https://doi.org/10.48433/cr_msm115

MSM116

MeBo deep-sea drilling on the Stocks Seamount, Equatorial Atlantic

Authors

Center for Marine Environmental Sciences (MARUM), University of Bremen | Bremen, Germany

H. Pälike, T. Bickert, and Scientific Party MSM116

Cruise Summary

The primary objective of MSM116 (was to obtain deposits of well-preserved calcareous microfossils with the MeBo200 coring device to allow the study of surface and bottom water temperatures, $\delta^{18}\text{O}$ -seawater, and related paleoceanographic parameters to establish climatic boundary conditions during past “warmer worlds”. The planned program consisted of coring two stations on the Rio Grande Rise (re-occupying DSDP Site 72–516), each triple-cored to obtain an as complete as possible sedimentary sequence from the Pliocene through at least the Miocene, but possibly older, strata. While deploying MeBo at the planned location, the Brazilian Navy prevented deployment, citing Articles 76 and 77 of the UN Convention on the Law of the Sea (UNCLOS) based on a claim as-of-yet unapproved by the Commission on the Limits of the Continental Shelf (CLCS). Instead, MSM116 conducted a site characterization and MeBo deployment on the Stocks Seamount in the Western Equatorial Atlantic, implementing the initial objectives at this alternate site. Overall, the material serves to establish a Paleogene sequence with good microfossil preservation, and to sample enough material to allow pairwise application of traditional and novel proxies to answer questions about the evolution of ocean temperatures, past CO_2 concentrations, and Earth System Sensitivity. Additionally, we conducted detailed multibeam mapping and subbottom parametric profiling to enhance our understanding of the cored sediments and the working area. Several CTD/Rosette measurements were taken to characterize the oceanographic conditions and properties of the water masses bathing the relatively shallow drilling sites and therefore establish to what extent paleoceanographic proxies to be measured from the sediment cores can be used to establish past changes.

Revised Work Area

As the Brazilian Navy interdicted access to the original working area (DSDP Site 516), we searched for alternative sites that would allow operation of MeBo200 at suitable water depths and slopes. At first, we investigated a series of seamounts by multibeam mapping and Parasound profiling around 34° 37.5'S, 026° 16.68'W that had previously been visited and dredged by the Nathaniel B Palmer cruise NBP1808 but could not find any suitable sediment cover. We then sailed to a set of accessible seamounts (the Bahia/Stocks seamounts), approximately 300 nm from our planned destination port Recife. As summarized by Berndt (2023), the Bahia seamounts are situated within the eastern region of the Brazil basin and contain more than 45 peaks in three roughly parallel chains. Towards the southwest the Bahia chain is bounded by the Ferraz ridge. The seamount chains are striking approximately 140° west of the Pernambuco sea channel, changing to 125° in the east (Cherkis et al., 1992). According to Cherkis et al. (1992) this orientation might represent movement of the South American plate over one or several hotspot(s), leading to the formation of the seamounts, becoming inactive in the early Tertiary or in the late Paleocene. Towards the south, the Bahia seamounts are bordering the Bode Verde Fracture Zone. Previous cruises to the Bahia Seamounts were the CENTRATLAN programs conducted by NRL and DHN 1980-1989, the REMAC projects in the 1970s, German expeditions 1925-1927 and 1938-1939 (Cherkis et al., 1992) and two Russian expeditions with the RV Akademik Sergei Vavilov 2009 and RV Akademik Ioffe (Skolotnev et al., 2010). The later sampled rocks from the Stock seamount by dredging, which turned out to be igneous rocks, limestone and Fe-Mn-Crusts (Skolotnev et al., 2010). The $^{40}\text{Ar}/^{39}\text{Ar}$ of the igneous rocks was measured to be 62 ± 4 Ma (Skolotnev et al., 2010).

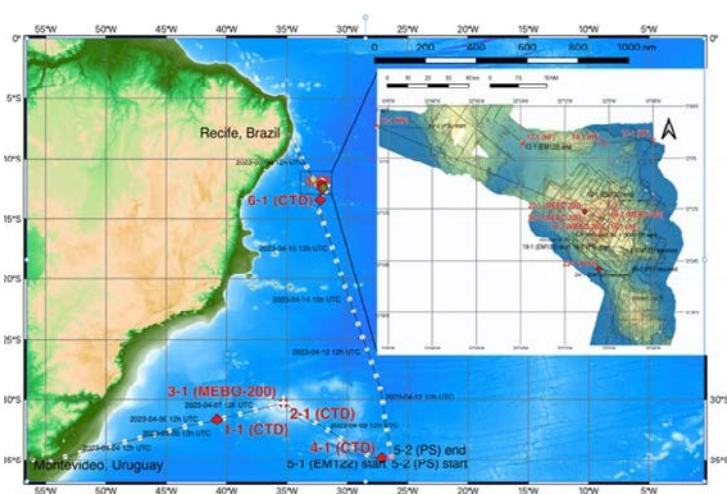


Figure 1: Track chart of RV MARIA S. MERIAN Cruise MSM116. Inlet is the main operational area on Stocks Seamount (part of the Bahia seamount chain) where MeBo200 was deployed.

Bathymetry and Sub-bottom profiling

During cruise MSM116 hydroacoustic measurements were important to determine suitable drilling locations for the MeBo200 drill deployment, considering the restrictions of the device to water depth and slope and the occurrence of sediments, as well as internal sedimentation structures. To characterize the seafloor morphology the ship-mounted KONGSBERG EM122 MBES was utilized. The ATLAS PARASOUND PS70 was used to image the sub-bottom structures. Ship speed on surveys was limited to 6kn to provide good resolution for both the Multibeam Echosounder and the Parasound. The bathymetric data on the Bahia Seamounts mainly cover the Stocks Seamount. The shallowest point of the Stocks Seamount is at a depth of 1475m.

The seamount consists of two prominent nearly circular plateaus, the lower of the two around 2000m deep, while the shallower plateau is at 1500m. The plateaus are confined by steep slopes up to 40°. The shallow plateau has an elongated feature towards the Northwest. Backscatter images of the Stocks Seamount show low energy at the plateaus while high energy channel like structures can be observed at the slopes. The elongated feature towards the Northwest also has high backscatter energy.

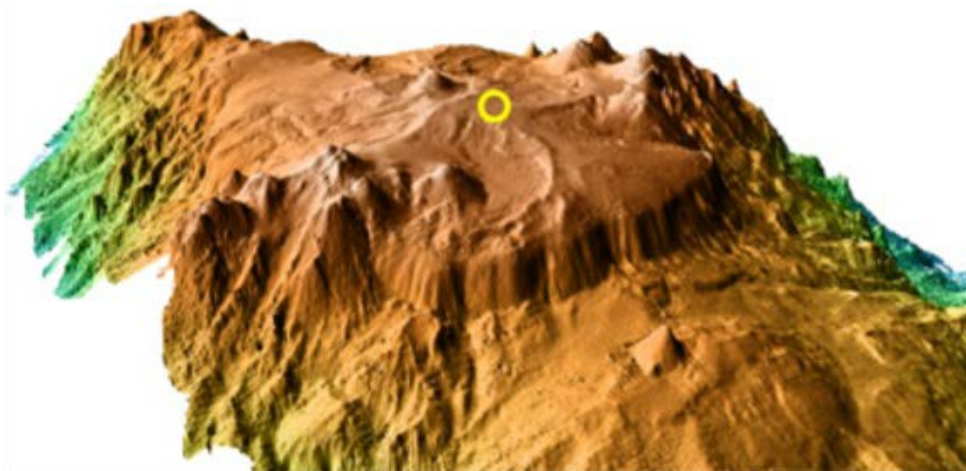


Figure 2: MSM116 Multibeam mapping of Stocks Seamount, view to North. The length of the plateau is about 10 nautical miles (figure with large vertical exaggeration). The plateau is at about 1600m water depth (yellow circle marks approximate MeBo200 location GeoB25308-1).

The sediments recovered consisted of almost pure foraminiferal sands with nannofossils and smaller fractions of foraminiferal ooze with nannofossils. Thus, on the one hand we had achieved our major aim of recovering well preserved carbonate rich sediments, while on the other hand these same pure foraminiferal

sands proved to be a challenge of recovery, not just for MeBo200, but probably most drilling operations that cannot deploy a casing.

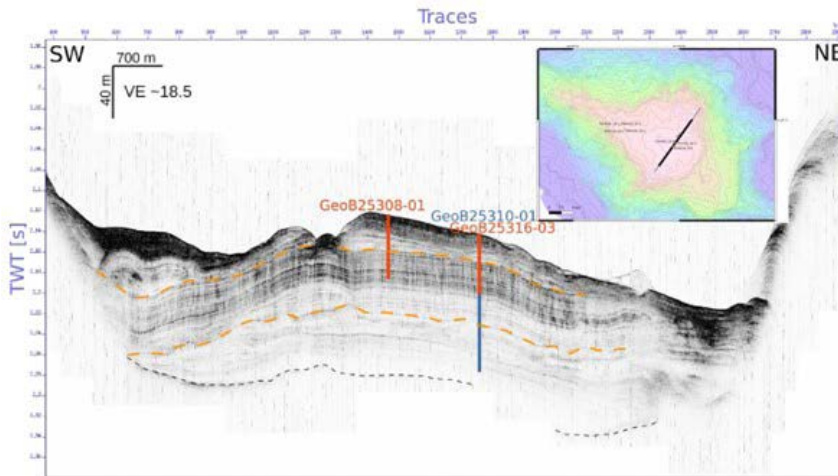


Figure 3: Parasound profile 21 across MeBo Stations GeoB250308-01, GeoB25310-01 and GeoB25316-03. Black dashed line shows acoustic basement, orange dashed line indicates boundary of distinct acoustic packages. Depths of the MeBo drillings was estimated with a sonic velocity of 1600 m/s.

References

Berndt P, Geoscientific Project – Application of Open-Source software in Marine Geophysics during MSM116, unpublished report, 2023, University of Bremen.

Cherkis N, Chayes D & Costa L, The bathymetry and distribution of the Bahia Seamounts, Brazil Basin. *Marine Geology* 1992, 103(1), 335–347, doi:10.1016/0025-3227(92)90024-C.

Pälike H, et al., MeBo deep-sea drilling of Pliocene through Oligocene sediments on the Rio Grande Rise, Cruise No. MSM116, 03.04.–07.05.2023, Montevideo (Uruguay) – Recife (Brazil), MARIA S. MERIAN-Berichte, MSM116 2024, Begutachtungspanel Forschungsschiffe, pp. 1–62, doi:10.48433/cr_msm116.

Skolotnev SG, Peive AA, Eskin AE, Petrova VV & Patina IS, New Data on the Rock Composition of the Bahia Seamounts (Brazil Basin, South Atlantic Ocean), *Doklady Earth Sciences* 2010, 435, 1569–1574, doi:10.1134/S1028334X10120044.

Scientific Output

List of Publications

Berndt P, Geoscientific Project – Application of Open-Source software in Marine Geophysics during MSM116, unpublished report, 2023, University of Bremen.

Pälike H, et al., MeBo deep-sea drilling of Pliocene through Oligocene sediments on the Rio Grande Rise, Cruise No. MSM116, 03.04.–07.05.2023, Montevideo (Uruguay) – Recife (Brazil), MARIA S. MERIAN-Berichte, MSM116 2024, Begutachtungspanel Forschungsschiffe, pp. 1–62, doi:10.48433/cr_msm116.

Olushukwu E, Paleogene Evolution of the Southwest Atlantic Intermediate Waters, MSc Thesis 2024, University of Bremen.

Oluwagesun O, Western South Atlantic Neogene sedimentation and paleoclimate studied by physical properties and XRF scans, MSc Thesis 2024, University of Bremen.

Abhulimhen W, Cenozoic Evolution of the South Atlantic Intermediate Water – Development of Sedimentary Composition, MSc Thesis 2024, University of Bremen.

Data

Ship track data:

<https://doi.org/10.1594/PANGAEA.963652>

<https://doi.org/10.1594/PANGAEA.963658>

CTD data:

<https://doi.org/10.1594/PANGAEA.972620>,

<https://doi.org/10.5281/zenodo.14501356>

ADCP data:

<https://doi.org/10.1594/PANGAEA.962562>,

<https://doi.org/10.1594/PANGAEA.962731>

Thermosalinograph data:

<https://doi.org/10.1594/PANGAEA.968972>

Raw Multibeam bathymetry:

<https://doi.org/10.1594/PANGAEA.965752>

Parasound data:

<https://doi.org/10.5281/zenodo.14501843> (ASD)

<https://doi.org/10.5281/zenodo.14502834> (SGY)

<https://doi.org/10.5281/zenodo.14503059> (PS3)

MeBo core section summaries:

<https://doi.org/10.5281/zenodo.14500322>

MeBo visual core description (VCD):

<https://doi.org/10.5281/zenodo.14500352>

MeBo initial shipboard biostratigraphy:

<https://doi.org/10.5281/zenodo.14501251>

MeBo multi sensor core logging data (MSCL):

<https://doi.org/10.5281/zenodo.14500967>

MeBo core color linescan data:

<https://doi.org/10.5281/zenodo.14501100>

MeBo core thermal conductivity data:

<https://doi.org/10.5281/zenodo.14501012>

Heatflow data from 3.5m lance:

<https://doi.org/10.5281/zenodo.14501223>

Cruise Report

MSM116:

https://doi.org/10.48433/cr_msm116

MSM117

Western boundary circulation, flow-topography interaction and ecosystem impacts off Brazil

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

R. Hummels, M. Dengler, P. Brandt

The main aim of R/V *MARIA S. MERIAN* cruise MSM117 was to study the variability of the western boundary current system off South America and to assess the strength and variability of the Atlantic meridional overturning circulation (AMOC) at 11°S. Particular emphasis was placed on the transport variability of the North Brazil Undercurrent (NBUC) within the framework of the AMOC and the Subtropical Cells (STCs), as well as the Deep Western Boundary Current (DWBC), on time scales ranging from intraseasonal to decadal. Additional insights into signal propagation along and across the equator were obtained from the meridional section at 35°W and the mooring operations at 23°W at the equator. These activities also supported the EU project TRIATLAS (“Tropical and South Atlantic climate-based marine ecosystem predictions for sustainable management”), which included supplementary observations along the Brazilian shelf and above two seamounts. Here, the focus was on flow-topography interactions, their influence on biogeochemical conditions, and the impacts for the local ecosystem. The Cape Verde Ocean Observatory (CVOO) mooring – which was also serviced on this cruise – represents a key element of the collaboration between GEOMAR and Cape Verde within the framework of the Ocean Science Centre Mindelo (OSCM). A central objective of this observatory is to advance the understanding of the role of mesoscale eddies, in particular their impact on the ocean’s CO₂ source/sink dynamics and the biological carbon pump in coastal upwelling regions.

Meridional Overturning and western boundary circulation in the tropical Atlantic

The circulation system in the Atlantic transports large amounts of heat as part of the Atlantic meridional overturning circulation (AMOC). AMOC variability is known to be to a large extent responsible for the mean climate state in the Atlantic sector on decadal to multidecadal time scales. Across the tropical Atlantic, interannual climate variability and associated rainfall variability has a multifaceted socio-economic impact on the countries from adjacent continents [Foltz *et al.*, 2019].

One of the key regions of the wind-driven and thermohaline circulation of the Atlantic Ocean is the western boundary current (WBC) system off Brazil. This region serves as a crossroads for the important meridional transfer of warm and cold water masses that are part of the AMOC as well as of the subtropical cell (STC). Accordingly, the upper ocean flow at the western boundary within the North Brazil Undercurrent (NBUC) can be decomposed into contributions from the AMOC, the southern wind-driven STC, and the Sverdrup related transport [Schott *et al.*, 2005].

During MSM117 the long-term monitoring effort, which has been implemented with the mooring array at the western boundary at 11°S consisting of 4 full-depth moorings along the Brazilian shelf, was serviced. This array is in place now since 2013 and was in the water in a similar setup also between 2000 and 2004. From these observations the transport time series of the NBUC (upper about 1200m depth) and the Deep Western Boundary Current (DWBC, between about 1200m and 3500m depth) are estimated and with the data of MSM117 the time series could be prolonged until May 2023 (Figure 1). Previously, time series of NBUC transport variability spanning several decades were estimated from historical hydrographic observations by Zhang *et al.* [2011]. In their study, multidecadal NBUC variability has a range of about 6.7 Sv. However, evidence for such strong multidecadal NBUC variations from direct current observations are still pending and can not be reported based on the direct current observations as presented here (Figure 1), where the NBUC seems rather stable on multidecadal time scales (basically no trend detectable over the 10-year period).

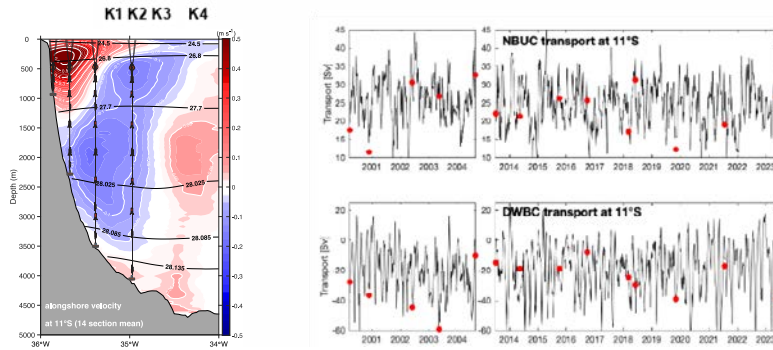


Figure 1: Left: Average section of alongshore velocity from shipboard observations determined from 14 full-depth sections at 11°S, where mooring positions and design are indicated with respect to the mean circulation. Right: Transport time series (update from Hummels et al. [2015]) of the moored array for the NBUC (upper panel) and DWBC (lower panel). Red dots mark transports estimated from shipboard observations.

In the context of investigating the variability of the AMOC at 11°S the pressure inverted echo sounders (PIES) at 300m and 500m isobaths at the western boundary were also serviced on MSM117. This data enabled – together with the bottom pressure data from the eastern boundary – the prolongation of the AMOC anomaly time series until May 2023, which now also consists of a 10-year record. As previously evidenced in *Herrford et al.* [2021], the seasonal cycle clearly dominates this timeseries (Figure 2) with peak-to-peak amplitudes of 7 Sv for the Ekman transport, 12 Sv for the upper-ocean geostrophic transport, and 14 Sv for the AMOC transport (Figure 2).

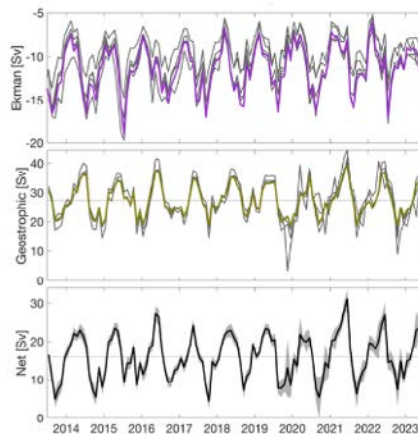


Figure 2: Basin-wide AMOC transport (component) time series in the upper 1200m (courtesy A. C. Hans). Upper panel: Ekman transport derived from ERA5, grey lines indicate uncertainty introduced by using different wind products. Middle panel: Geostrophic transport time series based on bottom pressure observations, grey lines indicate uncertainty introduced by various choices in the method e. g. vertical interpolation scheme etc. Lower panel: AMOC anomaly time series combining Ekman and geostrophic transport components.

This time series will be further analyzed together with the NBUC and DWBC transport time series and other available data sets such as e. g. Argo and sea level anomaly (SLA) products providing the most comprehensive AMOC estimate as possible from the available observations.

In order to relate the variability observed at the western boundary to the variability in the eastern equatorial Atlantic in the context of tropical Atlantic climate variability, the extending NBUC time series will be analyzed in combination with the transport time series of the Equatorial Undercurrent (EUC) obtained at 23°W at the equator, where the horizontal velocity field is monitored since 2002. This mooring was also serviced during MSM117 and the prolonged time series of upper ocean velocities until 2023 was used in a study investigating the interaction of the interannual variability of the equatorial currents, the intensity of tropical instability waves (TIWs) and sea surface temperatures in the eastern Atlantic or more precisely the Atlantic Niño region [Tuchen *et al.*, 2024]. Within this study, the developing 2021 Atlantic Niño (a warm event) led to weaker equatorial surface currents and hence to a reduction of the vertical shear of upper-ocean horizontal velocity, probably leading to reduced vertical mixing thereby amplifying the warm event. The observed strong reduction of the surface flow, eddy flux, and meridional temperature gradient in May then caused an extremely weak and delayed TIW season. Interestingly, the reduced meridional TIW advection then contributed to sharpen the north equatorial Chlorophyll-a front resulting in modest intraseasonal Chlorophyll-a variability.

Changes of water mass characteristics in the western tropical Atlantic

Variability of meridional freshwater fluxes represents an important mechanism for the variability and stability of the AMOC [Stommel, 1961]. Observations at the western boundary show increasing salinity over the past decades within the NBUC region as reported by Biastoch *et al.* [2009]. Biastoch *et al.* [2009] obtained a salinity trend of +0.028 per decade between 1965 and 2005 from available observational data off Brazil between 100 and 600 m depth, which is an ongoing trend as shown in Hummels *et al.* [2015] analyzing salinity trends on isopycnals at 5°S and 11°S contrasting the 2013–2014 observations to the period 2000–2004.

In order to investigate how such changes spread along isopycnals not only between the zonal sections along 5°S and 11°S, but also how and where they enter the equatorial current system, the hydrographic sections at 5°S, 11°S and at 35°W (the latter crossing the equator) were repeated during MSM117 and will be analyzed together with previously obtained hydrographic sections.

In addition to the hydrographic section along 35°W eight surface drifters were deployed along this section between about 2°25.2 S and the equator to

investigate the surface flow within the region. Unexpected eddying structures of the surface drifters were immediately observed after their deployment and were further analyzed in the Master thesis of Alexandra Andrae. Her analysis focused on equatorial Yanai waves as the possible source of the observed behavior of the drifters. Indeed, by combining Yanai wave velocities with local surface currents optimal initial conditions to mimic the behavior of the drifters could be determined.

Flow-topography interaction and its impact on the ecosystem

The Brazilian northeast continental shelf has a complex bottom topography with the presence of canyons and submarine channels, of which some can be found in the southern part of the Pernambuco shelf. The interaction between the strong WBC and topography along the Pernambuco Plateau is hypothesized to produce shelf-break upwelling and mixing. Likewise, oceanic currents and seamounts can interact, where the presence of seamounts transforms part of the kinetic energy in potential energy, promoting orographic upwelling, vertical mixing and nutrient enrichment. The nutrient enrichment leads to the fact that seamounts, islands and continental shelf breaks are open ocean hot spots of marine biodiversity [Morato *et al.*, 2010] and hence these regions are important in a social and economic sense as they are responsible for a large part of the catch of pelagic species off Northeastern Brazil. Even though these hot spots of marine biodiversity such as the Toninha and Aracati Bank are so important, they are up to now only poorly studied. For these reasons we performed combined measurements of the hydrography (CTDs and underway CTD), the current field (shipboard ADCPs), mixing intensity and resulting nutrient fluxes (microstructure measurements combined with nutrient observations from the CTD), zooplankton abundance and classification (UVP, multinet) as well as Chlorophyll-a, cytometry and phytoplankton flora (water samples and filters) on dedicated stations along the Brazilian shelf and over two seamounts at the Toninha and Aracati Bank respectively. While some of these data sets still need to be fully processed, it is planned to combine the physical and biogeochemical measurements to gain more insights into the interplay of the different physical and biogeochemical factors shaping these hot spots of biodiversity.

References

Biastoch A, Böning CW, Schwarzkopf FU & Lutjeharms JRE, Increase in Agulhas leakage due to poleward shift of Southern Hemisphere westerlies, *Nature* 2009, 462(7272), 495–498, doi: 10.1038/nature08519.

Foltz GR, Brandt P, Richter I, Rodriguez-Fonseca B, et al., The Tropical Atlantic Observing System, *Frontiers in Marine Science* 2019, 6(206), doi: 10.3389/fmars.2019.00206.

Herrford J, Brandt P, Kanzow T, Hummels, R, et al., Seasonal variability of the Atlantic Meridional Overturning Circulation at 11°S inferred from bottom pressure measurements, *Ocean Science* 2021, 17(1), 265–284, doi: 10.5194/os-17-265-2021.

Hummels R, Brandt P, Dengler M, Fischer J, et al., Interannual to decadal changes in the western boundary circulation in the Atlantic at 11°S, *Geophysical Research Letters* 2015, 42(18), 7615–7622, doi: <https://doi.org/10.1002/2015GL065254>.

Morato T, Hoyle SD, Allain V & Nicol SJ, Seamounts are hotspots of pelagic biodiversity in the open ocean, *Proceedings of the National Academy of Sciences* 2010, 107(21), 9707–9711, doi: 10.1073/pnas.0910290107.

Schott FA, Dengler M, Zantopp R, Stramma L, et al., The shallow and deep western boundary circulation of the South Atlantic at 5–11°S, *Journal of Physical Oceanography* 2005, 35(11), 2031–2053, doi: <https://doi.org/10.1175/JPO2813.1>.

Stommel H, Thermohaline Convection with Two Stable Regimes of Flow, *Tellus* 1961, 13(2), 224–230, doi: <https://doi.org/10.1111/j.2153-3490.1961.tb00079.x>.

Tuchen FP, Perez RC, Foltz GR, Brandt P, et al., Modulation of equatorial currents and tropical instability waves during the 2021 Atlantic Niño, *Journal of Geophysical Research: Oceans*, 2024, 129, e2023JC020431, doi: <https://doi.org/10.1029/2023JC020431>

Zhang D, Msadek R, McPhaden MJ & Delworth T, Multidecadal variability of the North Brazil Current and its connection to the Atlantic meridional overturning circulation, *Journal of Geophysical Research: Oceans* 2011, 116(C4), doi: <https://doi.org/10.1029/2010JC006812>.

Scientific Output

List of Publications

Tuchen FP, Brandt P, Hahn J, Hummels R, et al., Data product of full-depth current velocity observations at 0°N, 23°W from 2001-2023 (v2.0), PANGAEA, <https://doi.org/10.1594/PANGAEA.963935>.

Tuchen FP, Perez RC, Foltz, GR, Brandt, P, et al., Modulation of equatorial currents and tropical instability waves during the 2021 Atlantic Niño, Journal of Geophysical Research: Oceans, 2024, 129, e2023JC020431, doi: <https://doi.org/10.1029/2023JC020431>.

Andrae A, Observed eddying structures in the western equatorial Atlantic, Master thesis, 2024, Christian-Albrechts-Universität Kiel, Kiel, Germany, 83 pp.

List of conference presentations

2025 | **Variability of the Western Boundary Circulation at 11°S** EGU General Assembly, Vienna, Austria.

2025 | **Uncertainty evaluation of the AMOC transport calculation at 11°S** EGU General Assembly, Vienna, Austria.

2025 | **Variability of the Western Boundary Circulation and AMOC in the tropical Atlantic: Insights from in-situ observations** Helmholtz Topic 2 Seminar, online.

2024 | **Observed variability of the AMOC transport components at 11°S** EGU General Assembly, Vienna, Austria.

2023 | **Observations of the Boundary currents and AMOC at 11°S – the TRACOS array** | UGG General Assembly, Berlin, Germany.

2023 | **MSM117: Circulation, flow-topography interaction and ecosystem impact** VIII Seminar of the Bilateral Cooperation DOCEAN-GEOMAR, Recife, Brazil.

Data

Physical oceanography (Bathymetry):
<https://doi.pangaea.de/10.1594/PANGAEA.965757>

Physical oceanography (vmADCP, 38 kHz):
<https://doi.pangaea.de/10.1594/PANGAEA.964687>

Physical oceanography (vmADCP, 75 kHz):
<https://doi.pangaea.de/10.1594/PANGAEA.964686>

Physical oceanography (Mooring@0°N,23°W):
<https://doi.pangaea.de/10.1594/PANGAEA.963461>

Physical oceanography (CTD):

https://osis.geomar.de/app/expeditions/361685/files#:~:text=msm_117_1_ctd_rel4.zip

Physical oceanography (Microstructure):

https://osis.geomar.de/app/expeditions/361685/files#:~:text=MSM117_microstructure

Physical oceanography (SVP Drifter): WMO-IDs:

3101574, 3101575, 3101576, 3101577, 3101578, 3101579, 3101580, 3101581,
3101582, 3101583, 3101584

Cruise Report

MSM117: https://doi.org/10.48433/cr_msm117

MSM118

Paleoclimate and Biogeochemistry Nova Scotia 2.0 | MSM 118 NOVAMAR 2.0

Author

Institute of Geosciences, Kiel University | Kiel, Germany
H. Kolling

Cruise MSM118 NOVAMAR 2.0 was dedicated to the revisit of the southeast continental margin of Canada, in order to accomplish the part of the research program that had to be cancelled from the original cruise proposal when carrying out cruise MSM101 NOVAMAR under Covid19 limitations in 2021. Hence the biogeochemical program for the water column and water sediment interface were the major targets for MSM118 NOVAMAR 2.0, a 16 days cruise starting in Ponta Delgada, Azores, and ending in St. John's, Newfoundland (Figure 1). Except for one deeper coring station, we executed a few additional Holocene sediment coring sites. These were accompanied by short hydroacoustic surveys within inner shelf basins missed during MSM101 in 2021.

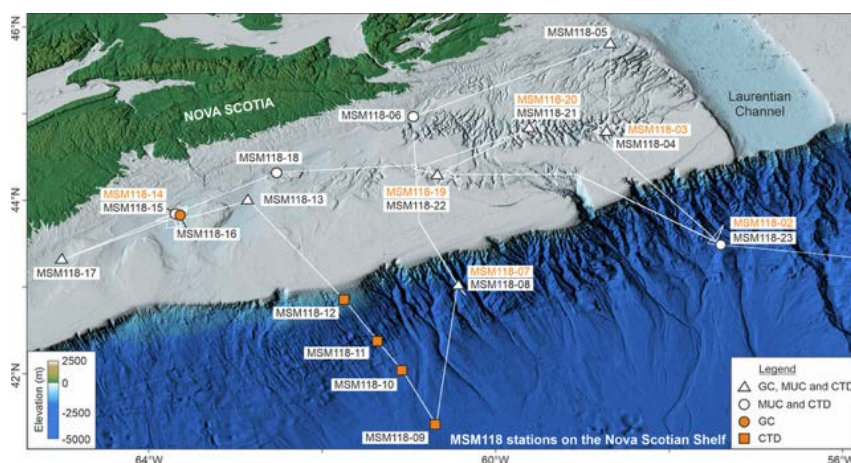


Figure 1: MSM118 cruise track (white line) with geological and water column sampling stations. White and orange triangles, circles and squares identify the gears deployed at each site labeled with station numbers.

The sampling program executed for water column and sediment biogeochemistry as well as short multicore and gravity coring for Deglacial to Holocene sediment sequences off Nova Scotia and Newfoundland aimed to understand past climate variability at high resolution and element fluxes between the water-column and underlying sediments. Particularly, the biogeochemical sampling of the water column and Holocene sediments should provide new information on the exchange of particulates, nutrient fluxes and gases between the different water masses, e. g. warm Atlantic Current and cold Labrador Current at the surface, the Nova Margin Slope Water at intermediate depths, and the surface sediments at the bottom (Figure 2).

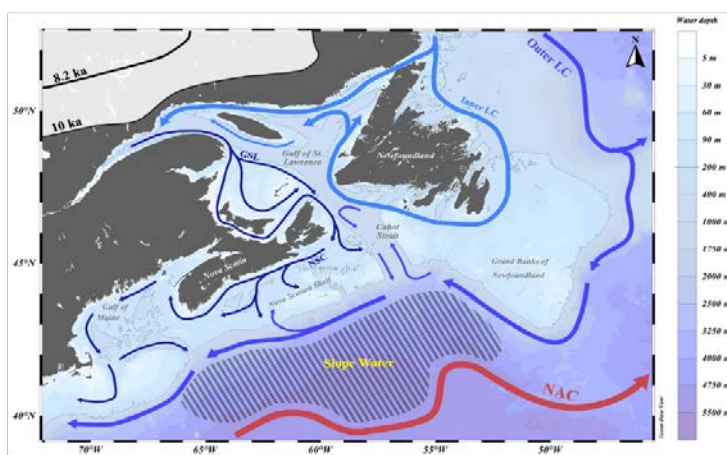


Figure 2: Location map of the Nova Scotian and Newfoundland region with recent surface circulation pattern and reconstructed LIS retreat. Cold currents (blue) on the eastern Canadian margin are shown delineating the Gulf of St. Lawrence waters (GSL), the Nova Scotian Current (NSC), and the inner and outer Labrador Currents (LC). The North Atlantic Current (NAC) transports warm waters (red) northeast-wards also in greater water depths (Matzerath et al. under review for QSR).

Preliminary post-cruise results, based on radiocarbon-derived age models, suggest that sediment deposition on the Scotian Shelf occurred entirely after deglaciation – commencing in the southwest around 14 ka and in the northwest around 9–10 ka. Porewater geochemical evidence indicates reduced salinities during the early and mid-Holocene, implying enhanced freshwater influence, likely due to strong meltwater discharge or diminished marine inflow under low sea-level conditions. Initial Nd isotope data further question earlier hypotheses proposing Slope Water incursion onto the Scotian Shelf.

Scientific Output

List of Publications

Matzerath P, Kolling H.M, Kienast M, Fahl K, Stein R, Gross F & Schneider R, Holocene sea-ice and productivity changes on the Scotian Shelf, NW Atlantic, accepted for publication at Quaternary Science Reviews.

Data

Current Velocities (ADCP; 75kHz):
<https://doi.org/10.1594/PANGAEA.964691>

Current Velocities (ADCP; 38kHz):
<https://doi.org/10.1594/PANGAEA.964689>

Underway temperature and salinity (Thermosalinograph):
<https://doi.org/10.1594/PANGAEA.972382>

Bathymetry (Multibeam):
Will be made available via DAM after the moratorium.

Sediment Echo Sounding (Parasound):
Will be made available via DAM after the moratorium.

Physical oceanography (CTD) and water column chemistry:
Will be made available on behalf of the late Prof. Markus Kienast by Prof. Stephanie Kienast

Geochemical Data:
Will be made available via Pangea.de by Prof. Florian Scholz

Cruise Report

MSM118: https://doi.org/10.48433/cr_msm118

MSM119

Ridge Flank Observatory Research south of Iceland using seafloor drilling

Authors

MARUM, University of Bremen| Bremen, Germany

A. Kopf

and Shipboard Science Party MSM119

Research cruise MSM119, also known as RIFLOR-2, set out to further investigate sedimentary ponds and crustal ridges along the eastern flank of the southernmost tip of the Reykjanes Ridge, Mid-Atlantic Ridge. Based on site-survey work during cruise M183 (2022) on RV Meteor, the MARUM MeBo70 seafloor drill rig represented the main workhorse on expedition MSM119. In general, the research focuses on the relevance of hydrothermal circulation in the flanks of oceanic ridges, and in particular of young basaltic crust with low sediment cover on the Reykjanes Ridge south of Iceland.

The main results of cruise MSM119 include:

- Successful installation of 4 MeBo borehole observatories in a total of 9 holes drilled in 1.500–1.700 meters of water depth, with a total penetration of 242 meters below seafloor and an average core recovery of 44%. The sediments were hemipelagic muds to coarse sands with occasional dropstones. At the contact to the basement, the sediment appeared cemented or otherwise diagenetically altered, potentially a mixture between thermal alteration and precipitation of authigenic phases. In two locations, basalt was recovered. The rocks were characterized by small (<1 mm) pores beneath their glassy contact surface and occasional fissures and fractures, some of which showed precipitated carbonate minerals (calcite, siderite).
- Recovery of 19 gravity cores to characterise sediment in the recharge and discharge ends of Squid Pond and along a transect of very young (ca. 0.76 Ma) to ca. 3.27 Ma old crust on the Reykjanes Ridge. The lithology is widely ranging

from mud to very coarse sands (often >2mm grain size). While in the bluish and the dark brown sections the material is finer (mud to silty mud), the light brown to reddish sections go up to larger grain sizes (sand). All the cores are highly influenced by bioturbation and many sections contain carbonate shells and dropstones. Fiber structures (spiculae) were observed in some layers that consist of mud to silty mud and appear in different sizes (approximately 0.5cm or 1.5–2cm).

Some core sections exhibit unique features, which were used for correlation between different cores has been conducted based on specific sediment layers like glass accumulations, very coarse-grained material (>2mm) often containing carbonate shells, layers of accumulated black grains, fiber structures (spiculae) and distinct sand layers of a few centimeters thickness.

Gravity cores taken from locations with similar topography show comparable features. Some cores were purposefully taken with very little sediment cover on top of the crust to sampler the volcanic glass and smaller chards deposited during ocean crust formation. The continuous, high-resolution (2,000-year) geochemical record of volcanic glass shards preserved in marine sediments encompasses glacial Terminations I and II and show temporal variations in incompatible elements and ratios that track glacial cycles, with increases during deglaciation best explained by changes in mantle melting extent. Periodic changes in MgO further indicate the influence of magma differentiation. Cross-correlation with benthic $\delta^{18}\text{O}$ and sea level records reveals an 8,000–1000-year lag, likely reflecting melt transit time. Our results provide direct evidence that rapid sea level changes affect ocean ridge magmatism through both mantle melting and crustal processes.

Initial results from the MSM119 sediment core and onboard geochemical analyses supported the findings of M183 on several location on the Reykjanes Ridge Flank, outside of Squid Pond. Close to the basement, the sediments show upward oxygen diffusion due to low-temperature hydrothermal circulation. In sediment ponds, geochemical conditions are more producing, showing preserved oxic layers.

- 89 deployments of a T gradient lance; but results did not reveal a significantly higher heat flow when approaching the ridge axis. However, for the sediment ponds between topographic highs, we could confirm directional recharge, flow and discharge of water in the upper basaltic aquifer. Data nicely complement our 4D approach using data from the in situ lances, borehole temperatures during MeBo drilling, and thermistors in the MeBo borehole observatories.
- Multibeam mapping of a wide area from spreading ridge axis to the Squid Pond at the southern Reykjanes Ridge (RR), including some selected PARASOUND profiling along the transects we sampled with gravity core and T-lance.

- 5 chain dredges taken along the strike of the RR axis to sample distinct age segments for basaltic crust and other rocks outcropping. Age transects included 0.05 Ma, 0.25 Ma, 0.75 Ma, 1.05 Ma, and 1.7 Ma old crust. Apart from the youngest transect, recovery was good and gave us a variety of basaltic rocks of different degree of alteration, with a few rare examples of vesicular basalt. Permeability of discrete samples tested for potential CO₂ injection varied from $1.55 \cdot 10^{-14} \text{ m}^2$ to $7.54 \cdot 10^{-21} \text{ m}^2$. In addition to basalts which we interpreted to be allochthonous, there was also a wide variety of sedimentary, metamorphic and other igneous rocks, which were interpreted to be glacially displaced and dropped in the study area.
- (Short-term) deployment of the MARUM developologic seafloor lander to monitor bottom water composition at a MeBo drill site with observatories.

References

Dzurisin D, A comprehensive approach to monitoring volcano deformation as a window on the eruption cycle, *Reviews of Geophysics* 2003, 41(1), 1.1–1.29, doi:10.1029/2001RG000107.

Schurr B, Asch G, Hainzl S, Bedford J, et al., Gradual unlocking of plate boundary controlled initiation of the 2014 Iquique earthquake, *Nature* 2014, 512, doi: 10.1038/nature13681.

Scientific Output

List of Publications

Kopf A, and AIMS³ scientific team, Initial Results of a Pilot Project for Sub-Seabed Basalt Storage of Carbon Dioxide on the Reykjanes Ridge, *Carbon Capture Science & Technology* 2024, 13, 100265. <https://doi.org/10.1016/j.ccst.2024.100265>.

List of conference presentations

2024 | **Technology Development, Field Assessments and Modelling Efforts for Sub-Seabed Basalt Storage of Carbon Dioxide on the Reykjanes Ridge, Mid-Atlantic Ocean** EGU Conference, Vienna, Austria.

2024 | **SPiraling Intelligent Robotic Underwater monitoring pLatform (SPIRULA)-
towards repeated, high density and low-cost seafloor monitoring** IEEE/OES
Autonomous Underwater Vehicles Symposium (AUV), San Francisco, USA.

2024 | **Dissolution experiments on a polyphase basalt surface under conditions
relevant to offshore CO₂ storage** EGU Conference, Vienna, Austria.

2025 | **Alternation of oxic and ferruginous intervals in pond sediments of
Reykjanes Ridge, North Atlantic Ocean** Goldschmidt Conference, Prague,
Czechia.

Data

Only some data sets (e. g. Multibeam bathymetry) have been uploaded to PANGAEA since the cruise was funded by EXC2077 and AIMS3 and a moratorium period was set. Publications are underway.

Cruise Report

MSM119: https://dx.doi.org/10.48433/cr_msm119

MSM120

Hudson Bay System Paleoceanography

Author

Kiel University | Kiel, Germany
R. Schneider

As one of the largest interior seas the Hudson Bay System (HuBS) is important for the freshwater budget of the Labrador Sea and western North Atlantic and thus plays an important role in deep water convection and northern hemisphere climate via interference with the thermohaline circulation. However, knowledge about the full impact of HuBS circulation changes, freshwater outflow versus Atlantic warm-water inflow, variance in winter sea-ice conditions, and CO₂ gas exchange with the atmosphere under varying climates is insufficient, particularly with respect to future consequences under global warming. Accordingly, expedition MSM120 was dedicated to water column and sediment sampling, hydroacoustic surveys and water mass chemistry. The new comprehensive data set should provide a better spatial and temporal coverage to investigate the changes in modern physical and chemical water column properties as well as in circulation in the HuBS at decadal to millennial time scales.

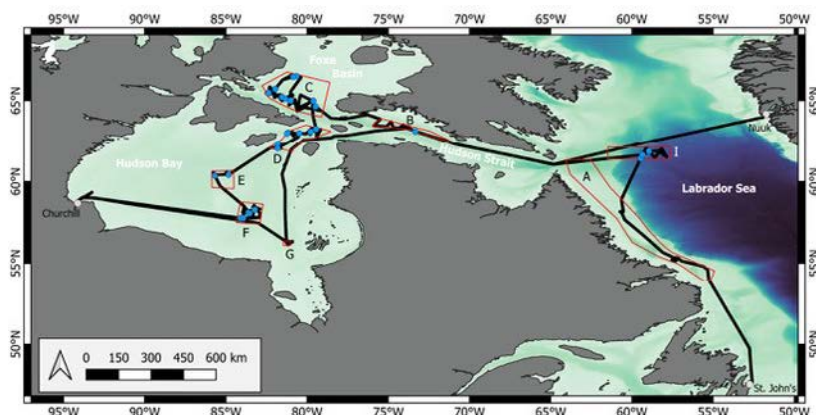


Figure 1: Final track chart of R/V Maria S. Merian cruise MSM120, with seven main working areas on the Labrador Shelf and Slope (Working areas A and I), in Hudson Strait Working Area B), as well as in Foxe Basin and Hudson Bay (Working Areas C, D, E, F, and G). Bathymetry from GEBCO 2023.

The investigation of the regional development and pathways of freshwater pulses into the North Atlantic Ocean was first priority, based on high-resolution multi-proxy studies based on Holocene sediment sequences with sound chronologies along the main freshwater routes in the HuBS. Therefore, expedition MSM120 and associated post-cruise work should improve our knowledge on the postglacial climatic development within the HuBS, i. e., Hudson Strait, Foxe Trough, Hudson Bay by studying i) early/mid Holocene proglacial freshwater outbursts recorded in Hudson Bay and Hudson Strait sediments, ii) documentation of Late Holocene freshwater events, and iii) recent to sub-recent and past changes in deep-water formation and estuarine circulation and related coastal ecosystem response. For this purpose, new short and long sediment cores from key locations were collected within eight work areas (see red boxes in Figure 1). Highest priority was given to areas that provide several meter thick, continuous and complete Holocene sediment sequences from contourite drift bodies on the one hand. In contrast, incomplete sediment piles with erosional features, e. g. sand and gravel layers winnowed for the fine fraction, should serve the identification of the timing of sediment hiatuses due to periods of stronger bottom water flow, e. g. periods of enhanced cold-water convection due to more intense HuBS sea-ice cover. Ample evidence for temporary Holocene sediment erosion and downward transport into the deeper basins is provided by the detailed hydroacoustic profiling in working areas C and D. The PARASOUND sediment echosounder data show the occurrence of contourite drift bodies at water depths, deeper than 350 m and 270 m in the Foxe Basin and the western Hudson Strait, respectively (Figure 2), most likely indicative of persistent near-bottom currents.

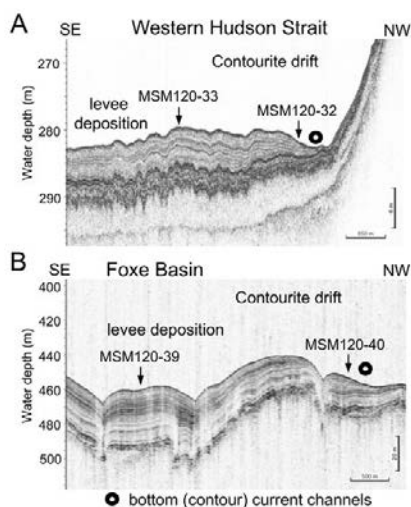


Figure 2: Examples of contourite drifts occurrence at rather great water depths of Western Hudson Bay (A) and Foxe Basin (B). At each drift one station was placed in or close to the bottom current channels and a second in the levee deposition centre (see cruise report MSM120).

First results from post-cruise work will be presented based on preliminary age models for the contourite sediment cores, covering only the last 6000 kyr BP, and from detailed sedimentological inspections within and outside the hiatuses identified closer to the erosional channels.

Scientific Output

List of conference presentations

2025 | **Strong winter-time deep-water formation during the Little Ice Age in subarctic semi-enclosed formerly glaciated marginal seas (Baltic Sea and Eastern Canadian coastal waters)** EGU 2025, Vienna, Austria.

Data

Master tracks MSM120, PANGAEA:
<https://doi.org/10.1594/PANGAEA.964020>

Hydroacoustic and hydrographic (CTD) data, stored on IOW server, contact:
svenja.papenmeier@io-warnemuende.de, thomas.neumann@io-warnemuende.de

Radiocarbon AMS data on mollusks from gravity cores, Data repository Leibniz Laboratory, Kiel University, contact:
ralph.schneider@ifg.uni-kiel.de

All other data will be accessible after a moratorium of five years on PANGAEA

Cruise Report

MSM120: https://doi.org/10.48433/cr_msm120

MSM122

Shaping the structure of fracture zones by magmatic activity at ridge-transform-intersections: constraints from bathymetric and magnetic data

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

I. Grevemeyer, L.H. Ruepke, F. Zhou

Institut de Physique du Globe & Université Paris Cité | Paris, France

J. Dyment

Institute of Geophysics, University of Hamburg | Hamburg, Germany

C. Hübscher

Oceanic fracture zones (FZ) are perhaps the most striking features in the ocean basins, especially in the Pacific Ocean where they were discovered by H. William Menard (1955) long before the theory of plate tectonics emerged. Seafloor mapping indicated that they are several thousand of kilometres long and have irregular topography, including “great seamounts, narrow troughs, asymmetric ridges and escarpments” (Menard, 1955) for which Menard coined the term “fracture zones”. He further noted that they follow small circles and found that they cover roughly 5% of the seafloor in the North Pacific. Plate tectonics placed fracture zones into a new framework, showing that they are generically related to oceanic transform faults (Wilson, 1965). Their tectonically active region is known today as an oceanic transform fault (OTF), where two tectonic plates move past each other (Wilson, 1965). Transform faults are one of the three major plate boundary types on the planet. Each oceanic transform is bounded by two ridge-transform intersections (RTI) where tectonic stresses rotate by tens of degrees over a very short distance (Morgan and Parmentier, 1994). RTIs separate normal faulting at the mid-ocean ridge (MOR) spreading axis from strike-slip faulting along the transform fault (Sykes, 1967). In the original framework of plate tectonics, transform faults are proposed to be conservative. Thus, once formed at an RTI, magmatic crust is supposed to traverse the transform with no further

modification and hence crust is neither formed nor consumed, becoming part of the fracture zone after passing the opposite RTI (Fox and Gallo, 1984).

Recent evidence, however, suggests that the traditional concept of transform faults as being conservative (non-accretionary) plate boundary faults might be wrong (Grevemeyer et al., 2021). Instead, numerical modelling results (Grevemeyer et al., 2021) and bathymetric data (Ren et al., 2022; Grevemeyer et al., 2021) suggest that (i) transform faults seem to suffer from extensional tectonics below their strike-slip surface fault zone and a global compilation of legacy bathymetric data suggests that (ii) ridge-transform intersections seem to be settings of magmatic activity, modifying the lithosphere and burying the transform valley before it passes into the fracture zone region. During MSM122, we went forward to test both hypotheses at the Oceanographer OTF to the south of the Azores by (i) revealing the displacement of the strike-slip fault using seafloor geodesy (direct path ranging) and (ii) studying the micro-seismicity and its relation to tectonic elements of the OTF (transform valley, strike-slip fault trace, bounding walls) with a network of long-term OBS and a seafloor geodetic network deployed for one year, which were recovered during M204 in October of 2024. These datasets are still under investigation. In addition, (iii) high-resolution bathymetric and magnetic data were acquired over the Oceanographer and Hayes transforms to obtain the magnetization of the basement of both the OTF and fracture zones, testing the newly proposed model of a two-phase crustal accretion (Grevemeyer et al., 2021; Guo et al., 2023) separated by a period of transform extension at OTFs. Here, we will report in detail the bathymetric data from the Oceanographer and the magnetic data from Hayes.

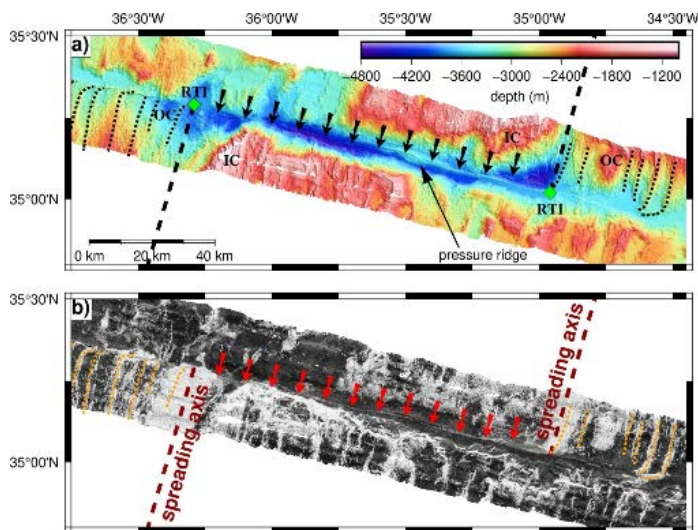


Figure 1: High-resolution EM122 seafloor bathymetry and backscatter intensity over the Oceanographer transform fault. Arrows mark the plate boundary fault (from Grevemeyer et al., 2025).

Over the Oceanographer OTF, the new multibeam data cover a roughly 10,000 km² large area, including both adjacent fracture zones and the intersections with the Mid-Atlantic Ridge. The active OTF is a 120 km long, up to 15 km wide and over 4000 m deep depression (Figure 1a). The valley is flanked by steep mountains or walls, which, at the inside corner highs, culminate in less than ~1500 m water depth. The greatest water depths of over 4500 m are reached in the nodal basins at the eastern RTI as well as the western half of the transform valley.

Based on a right-angular geometry at the intersection between the spreading axis and the transform fault, RTIs would occur at the centre and terminus of the median valley of the adjoining segments of the MAR (Figure 1). In the vicinity of both RTIs, the median valley shows a triangular shape. At the inside corners and most prominent in the vicinity of the eastern RTI (Figure 2a), a number of terraces and escarpments occur, showing evidence for down-slope land sliding and mass wasting. They do not parallel the trend of the spreading axis, but strike SW-NE. Near the summit, the morphology of SW-NE striking lineations indicates normal faulting and it is reasonable to suggest also the escarpments on the middle slope represent hanging walls of large normal faults. At the lower slope of the inside corner, some terraces strike parallel to the strike of the transform, showing a stairway-like morphology.

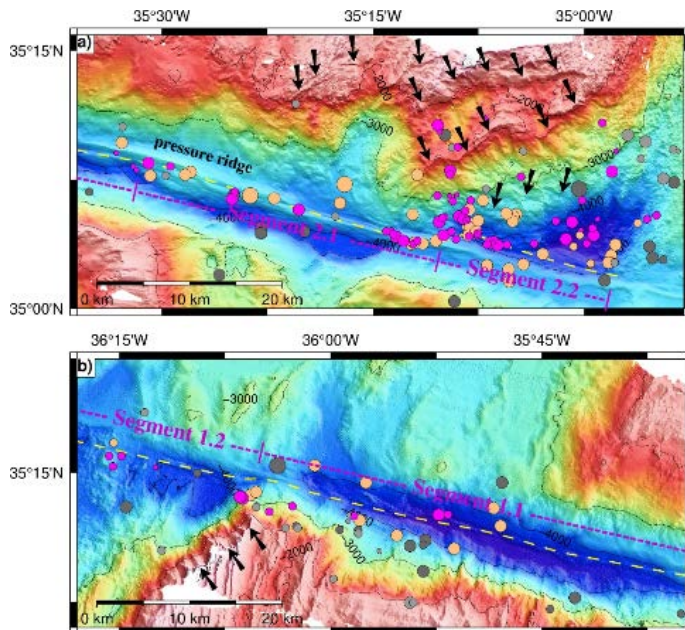


Figure 2: Detailed morphology of the two ridge-transform-intersections; dots mark epicentres of micro-earthquakes recorded by Grevemeyer et al. (2025); arrows mark observed normal faults and terraces.

The active transform fault runs within the deep transform valley. The shallowest setting within the valley is a pressure ridge-like feature near 35°20'W roughly halfway between the ridge transform intersections. It marks a segment boundary of shallower seafloor to the east and deeper seafloor to the west. On either side of the pressure ridge, the fault stretches out to the RTIs. Westward between 35°40'W and 36°W, the fault trace is composed of subparallel lineations or small subdued ridges. From the pressure ridge eastward, the fault strand is marked by an up to 500 m high (with respect to the surrounding valley floor) and up to 4 km wide ridge-like feature. This ridge is itself cut by up to 12 km long and up to 100 m deep grooves. The transform fault shows characteristic kinks where the inside corners impinge on the transform valley and hence the trace of the transform steps or curves towards the inside corners, forming secondary segment boundaries. Facing the MAR valleys, the fault strands show small subdued ridge-like morphology paralleling the strike of the transform. However, clear fault strands disappear approaching the RTIs. Before the fault approaches the western intersection with the MAR, the transform valley gets rugged and neither backscatter nor any well-defined bathymetric features clearly outline the fault trace. One interpretation might be that recent mass wasting products cover the active fault. Thereafter, higher backscatter outlining the fault strand moves towards the median valley of the adjoining western MAR segment. Here, a small bathymetric ridge defines the transform. Approaching the RTI, the fault trace disappears in the strong backscatter signal of recent volcanic activity.

In the vicinity of the RTIs, the seafloor is generally deepest where the MAR joins the transform valley, but towards the adjoining fracture zones the seafloor shallows rapidly. Near the western RTI, the transition is more gradual, but rather abrupt at the eastern RTI rising from ~4400 m to ~3500 m approaching the outside corner and the adjacent fracture zone valley. On either side of the active transform, we see a number of volcanic ridges approaching and sometimes intruding into the fracture zone. At the western fracture zone, they are well preserved, J-shaped and a common feature in the outside corner. These ridges basically extend across the entire fracture zone and terminate at the toe of the northern shoulder of the valley. Backscatter corroborates the interpretation of seafloor morphology. Thus, volcanic or J-shaped ridges show high backscatter and terminate on the older plate (Figure 1b), suggesting that some volcanic rocks erupted across the plate boundary onto the older plate. In general, J-shaped ridges cutting into the fracture zone show gaps between them suggesting they form episodically.

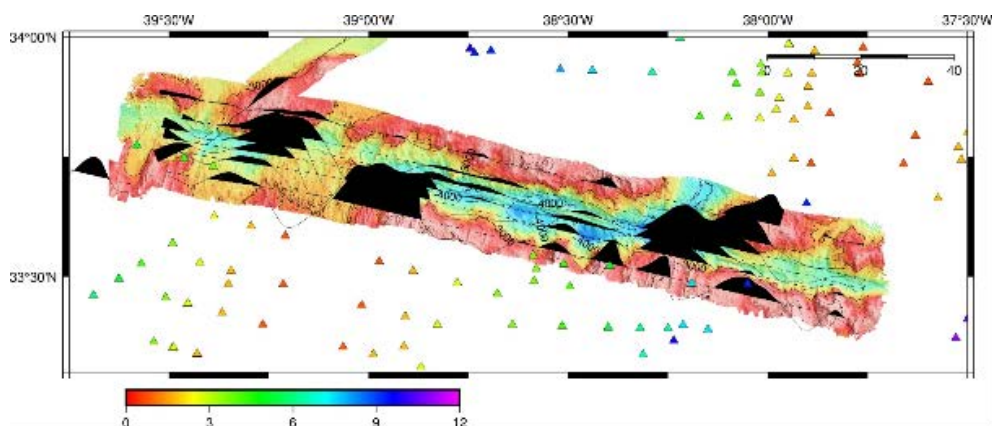


Figure 3: Background shows EM122 bathymetry and wiggles show recorded magnetic anomalies over the Hayes transform fault; coloured symbols mark seafloor age from of identified seafloor spreading anomalies (in Mio. Years).

The nature of overprinting the crust flooring of OTFs before entering the adjacent fracture zone domain is also clearly evidenced in magnetic data acquired over the Hayes OTF (Figure 3), offsetting the Mid-Atlantic Ridge by 70 km. The recorded magnetic data show rather subdued anomalies over the transform valley, but very prominent anomalies over the fracture zones facing the transform valley. A magnetic inversion of the recorded data revealed both at Oceanographer and Hayes that the crust in the fracture zone shows an increased magnetization of 3–5 A/m. Similar features are also observed at other slow and ultraslow spreading OTFs, supporting that a second phase of magmatic activity overprints magmatically starved crust at ridge-transform intersections.

References

- Fox PJ & Gallo DG, A tectonic model for ridge transform ridge plate boundaries - implications for the structure of oceanic lithosphere, *Tectonophysics* 1984, 104, 205–24, doi:10.1016/0040-1951(84)90124-0.
- Grevemeyer I, Ruepke LH, Morgan JP, Iyer K & Devey CW, Extensional tectonics and two-stage crustal accretion at oceanic transform faults, *Nature* 2021, 591, 402–407, doi:10.1038/s41586-021-03278-9.
- Grevemeyer I, Lange D, Klaucke I, Ruepke LH, Beniest A, Gómez de la Peña L, Ren Y, Filbrandt C, Hilbert H-S, Li Y, Murray-Bergquist L, Unger Moreno K, Hansteen T & Devey CW, Strike-slip versus extensional tectonics at the Oceanographer transform fault, Mid-Atlantic Ridge at 35°N, *Journal of Geophysical Research: Solid Earth* 2025, 130, e2024JB030880, doi:10.1029/2024JB030880.

Guo Z, Liu S, Rüpke LH, Grevemeyer I, Morgan JP, Lange D, Ren Y & Tao C, Disparate crustal thicknesses beneath oceanic transform faults and adjacent fracture zones revealed by gravity anomalies, *Geology* 2023, 51, 300–304, doi:10.1130/G50429.1.

Menard HW, Deformation of the northeastern Pacific Basin and the west coast of North America, *GSA Bulletin* 1955, 66, 1149–1198, doi:10.1130/0016-7606(1955)66[1149:DOTNPB]2.0.CO;2.

Morgan JP & Parmentier EM, Lithospheric stress near a ridge-transform intersection, *Geophys. Res. Lett.* 1984, 11, 113–116, doi:10.1029/GL011i002p00113.

Ren Y, Geersen J & Grevemeyer I, Impact of spreading rate and age-offset on oceanic transform fault morphology, *Geophys. Res. Lett.* 2022, 49, e2021GL096170, doi:10.1029/2021GL096170.

Sykes LR, Mechanism of earthquakes and nature of faulting on the mid-oceanic ridges, *J. Geophys. Res.* 1967, 72, 2131–2153, doi:10.1029/JZ072i008p02131.

Wilson JT, A New Class of Faults and their Bearing on Continental Drift, *Nature* 1965, 207, 343–347, doi:10.1038/207343a0.

Scientific Output

List of Publications

Grevemeyer I, Lange D, Klaucke I, Ruepke LH, Beniest A, Gómez de la Peña L, Ren Y, Filbrandt C, Hilbert H-S, Li Y, Murray-Bergquist L, Unger Moreno K, Hansteen T & Devey CW, Strike-slip versus extensional tectonics at the Oceanographer transform fault, Mid-Atlantic Ridge at 35°N, *Journal of Geophysical Research: Solid Earth* 2025, 130, e2024JB030880, doi:10.1029/2024JB030880.

Zhou F, Grevemeyer I, Dymant J, Ruepke LH & Huebscher C, Crustal magnetization over oceanic transform fault and adjacent fracture zones – evidence for magmatic activity at conservative plate boundaries, *Journal of Geophysical Research: Solid Earth*, in preparation.

List of conference presentations

2024 | **Modeling the Evolution of Transform Faults: Influence of Mid-Ocean Ridge Spreading Dynamics** Annual Meeting of the European Geoscience Union, Vienna, Austria.

2024 | **Faulting and magmatism at Atlantic ridge-transform intersections: Insights from new magnetic surveys** Fall Meeting of the American Geophysical Union, Washington, U.S.A.

2025 | **Oceanic transform faults and fracture zones “in modern dress”** Annual Meeting of the European Geoscience Union, Vienna, Austria.

Data

Master track (1 sec):

<https://doi.org/10.1594/PANGAEA.965484>

Master track (different resolution):

<https://doi.org/10.1594/PANGAEA.965483>

ADCP (75 kHz):

<https://doi.org/10.1594/PANGAEA.965954>

ADCP (38 kHz):

<https://doi.org/10.1594/PANGAEA.965953>

Thermosalinograph oceanography:

<https://doi.org/10.1594/PANGAEA.968981>

EM122 bathymetry (whole cruise):

<https://doi.org/10.1594/PANGAEA.965974>

Magnetic field measurements:

(submitted to PANGAEA)

Cruise Report

MSM122: https://doi.org/10.48433/cr_msm122

MSM123

Bubble Mediate Gas Exchange in the Labrador Sea (BELS)

Author

GEOMAR Helmholtz-Centre for Ocean Research Kiel | Kiel, Germany
C. A. Marandino

The air-sea transfer of poorly soluble gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and oxygen (O_2) is critical in regulating climate and ocean ecosystems (IPCC, 2023). For example, the ocean takes up approximately a quarter of the CO_2 emitted by humans (Friedlingstein et al., 2025), which diminishes its global warming effect, but also leads to ocean acidification (Doney et al., 2009). Understanding air-sea gas exchange is essential for assessing the global carbon budget, projecting the state and impact of future climate, and developing possible climate mitigation strategies, like marine carbon dioxide removal (mCDR; e. g., Doney et al., 2024). Air-sea exchange for low-solubility gases is limited by transfer in the waterside boundary layer and is further enhanced by bubble-mediated transfer beneath the surface (Liss & Slater, 1974). Wind-driven shear near the surface drives interfacial gas transfer, while wave formation and breaking introduces additional complexity, generating bubbles that exchange gas with the surrounding water (e. g., Woolf, 1993). However, quantifying bubble-mediated transfer remains challenging.

The Labrador Sea is a high latitude region of the ocean where open ocean deep convection and seasonal solubility and biology-driven changes occur faster than air-sea gas exchange can re-establish air-sea equilibrium. It is, consequently, one of the most intense sinks for carbon dioxide (CO_2) and oxygen (O_2) globally. The Labrador Sea is one of the few regions where winter open ocean deep convection occurs, promoted by rapid heat loss from the surface. Average surface temperatures (March–December) range from 2–10°C and surface wind speed reaches over 20 m s⁻¹ during winter storms. Deep convective mixing causes deepening of the seasonal mixed layer, reaching 2000 m during the winters of exceptionally large heat loss (Koelling et al., 2017). Subsiding winds and increased light lead to a shift to the productive season, which usually lasts from April to Mid-September. During the peak of the spring bloom in June, p CO_2 levels are

lowered 50 μatm below atmospheric causing a large air-to-sea influx. At the same time, oxygen reaches 117% saturation causing active oxygen outgassing from the surface. After the end of the productive season, surface waters cool down, increasing solubility of gases and causing undersaturated conditions favourable for oxygen uptake. Undersaturation is further fuelled by entrainment of deep oxygen-depleted waters. Contrary to oxygen, undersaturation of pCO_2 is compensated by entrainment of CO_2 -rich waters in December-March, when convection reaches deep ocean layers. The resulting CO_2 air-sea flux over the winter period hovers around zero (Atamanchuk et al., 2020).

Although it is clear that high-latitude regions are key for ocean-atmosphere transfer and sequestration in the deep ocean, our knowledge of the basic forcing mechanisms at play there remain very uncertain. Gas, momentum, and heat exchange are highly nonlinear functions of wind speed, indicating that mechanisms operating at high winds, such as bubble-mediated transfer, need to be constrained. Global change issues such as increasing temperatures, ocean acidification, and ocean deoxygenation are interlinked and in order to understand the changes in uptake, biogeochemical cycling, and feedback processes of environmentally important gases, mechanisms controlling their air-sea exchange must be understood. Bubble-mediated gas exchange is under-represented in models, in part due to a lack of mechanistic understanding and, thus, have limited ability to parameterise its contribution to the overall gas flux. As an indication, current model estimates of bubble contributions to global CO_2 flux range from approximately zero (Krall et al., 2019) to 40% (Deike et al., 2018; Reichl & Deike, 2020).

The overarching objective of BELS was to understand and quantify bubble-mediated gas exchange mechanisms. Special attention was given to the forcing and parametrisation of air-sea exchange for the insoluble gas O_2 . We employed a range of complementary techniques to tackle the questions posed, including continuous profiling and underway measurements, tracer release, noble gas measurements, and direct bubble characterisation. By combining these techniques, we have the major advantage of connecting bubble process understanding with comprehensive flow, gas saturation and gas flux measurements, and directly observing bubble-mediated gas uptake mechanisms. Here, we will present an overview of the work on board and a glimpse of the first results from BELS, including newly processed data from the bubble and SWIFT buoys, and AUVs. Preliminary gas distributions and dual tracer data will also be discussed. In addition, early results from a modelling initiative to reproduce measurements on board will be shown. Finally, the main remaining knowledge gaps related to bubble-mediated gas transfer, summarised in a recently submitted review article by BELS scientists, will be highlighted and a way forward proposed.

References

- Atamanchuk D, Koelling J, Send U & Wallace DWR, Rapid transfer of oxygen to the deep ocean mediated by bubbles, *Nature Geoscience* 2020, 13(3), 232–237, <https://doi.org/10.1038/s41561-020-0532-2>.
- Deike L & Melville WK, Gas transfer by breaking waves, *Geophysical Research Letters* 2018, 45(19), 10,482–10,492, <https://doi.org/10.1029/2018GL078758>.
- Doney SC, Lima I Feely RA, Glover DM, Lindsay K, Mahowald N, et al., Mechanisms governing interannual variability in upper-ocean inorganic carbon system and air-sea CO₂ fluxes: Physical climate and atmospheric dust, *Deep Sea Research Part II: Topical Studies in Oceanography* 2009, 56(8–10), 640–655, <https://doi.org/10.1016/j.dsr2.2008.12.006>.
- Doney SC, Wolfe WH, McKee DC & Fuhrman JG, The science, engineering, and validation of marine Carbon Dioxide Removal and storage, *Annual Review of Marine Science* 2024, 17(1), 55–81, <https://doi.org/10.1146/annurev-marine-040523-014702>.
- Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Hauck J, Landschützer P, et al., Global Carbon Budget 2024, *Earth Syst. Sci. Data* 2025, 17(3), 965–1039. <https://doi.org/10.5194/essd-17-965-2025>.
- IPCC: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)], IPCC 2023, Geneva, Switzerland, 184 pp., doi: 10.59327/IPCC/AR6-9789291691647.
- Krall KE, Smith AW, Takagaki N & Jähne B, Air-sea gas exchange at wind speeds up to 85 m s⁻¹, *Ocean Science* 2019, 15(6), 1783–1799, <https://doi.org/10.5194/os-15-1783-2019>.
- Koelling J, Wallace DWR, Send U & Karstensen J, Intense oceanic uptake of oxygen during 2014–2015 winter convection in the Labrador Sea. *Geophysical Research Letters* 2017, 44(15), 7855–7864, <https://doi.org/10.1002/2017GL073933>.
- Liss PS & Slater PG, Flux of gases across the air-sea interface, *Nature* 1974, 247(5438), 181–184, <https://doi.org/10.1038/247181a0>.
- Reichl BG & Deike L, Contribution of sea-state dependent bubbles to air-sea carbon dioxide fluxes, *Geophysical Research Letters* 2020, 47(9), e2020GL087267, <https://doi.org/10.1029/2020GL087267>.

Scientific Output

List of Publications

There are no publications yet.

List of conference presentations

2025| **Relationship between wave states and deep bubble plume formation in the open ocean (talk)** APS 77th Annual meeting of the Division of Fluid Dynamics, Houston, USA

2024| **A Holistic Approach to Ocean Observations for Process Understanding: Bubble-mediated Exchange in the Labrador Sea (poster)** Ocean Sciences Meeting, New Orleans, USA

2024| **Near surface bubble, gas and flow measurements during the Bubble Exchange in the Labrador Sea (BELS) cruise – early results (poster)** Ocean Science Meeting, New Orleans, USA

Data

Basic cruise data:

Map:

https://download.pangaea.de/reference/125404/attachments/MSM123_nav.png

Event list:

<https://www.pangaea.de/expeditions/events/MSM123>

Data:

<https://www.pangaea.de/?q=campaign:name:%22MSM123%22>

Master track:

<https://doi.pangaea.de/10.1594/PANGAEA.967497>

Cruise Report

MSM123: https://doi.org/10.48433/cr_msm123

M179

Fjord Flux: Dynamic Effects of glacial melting and human impact on fjordic ecosystems of the Beagle Channel and the Chilean fjord system of Southern Patagonia

Authors

Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany

B. Krock, C. Richter, F. Koch

Institute for Chemistry and Biology of the Marine Environment | Wilhelmshaven, Germany

J. Wollschläger

University of Rostock | Rostock, Germany

S. Forster

Universidad Austral de Chile | Valdivia, Chile

H. González-Estay, R. Giesecke-Astorga

Universidad de Concepción | Concepción, Chile

L. Castro-Cifuentes, M.J. Verdugo-Avello

Universidad Mayor | Santiago, Chile

N. Trefault-Carillo

Centro de Investigación en Ecosistemas de la Patagonia | Coyhaique, Chile

R. Torres-Saavedra

Instituto Argentino de Oceanografía | Bahía Blanca, Argentina

J. Garzón-Cardona

Centro Austral de Investigaciones Científicas | Ushuaia, Argentina

A. Malits

The cruise M179 “FjordFlux” was divided into two legs: The transit cruise M179/1 and the main cruise M179/2. With M179/1, the aim was to make scientific use of the necessary transit of RV METEOR to Punta Arenas as starting point for M179/2. In order not to negatively affect the transit time, only a limited scientific program in the form of underway oceanographic and ocean color measurements as well as regular sampling from the ship’s seawater system was carried out. From the samples, phycotoxins and vitamins, phytoplankton taxonomic composition and dissolved organic matter composition were determined.

Measured temperature along the transit was in a range from 13.02 to 28.61 °C with the highest values in equatorial waters, where also the highest values of salinity (~37 PSU) were found. While chlorophyll-a concentration was over the largest part of the cruise below 0.5 µg/L and increased only towards the end of the cruise significantly, turbidity was generally higher along the coast of South America than in the open Atlantic Ocean. All four parameters (temperature, salinity, turbidity, and chl-a) changed significantly after the mouth of the Rio de la Plata (approx. 35° S), indicating a change in water mass. This was also confirmed by a change in phytoplankton composition.

During 19 transects within the transit, paralytic shellfish toxins (PST) were detected only at low abundances of max. 6 pg/L seawater, which is the first record of these phycotoxins in the central Atlantic Ocean. Considering the different PST profiles, the detection of GTX2/3 (max. 5.4 pg/L) in the Gulf Stream area (possibly Brazil Current) indicated the presence of *Gymnodinium catenatum* or potentially *Centrodinium punctatum*. In contrast, the detection of GTX1/4 (max. 1.9 pg/L) at the last transects indicated the presence of *Alexandrium catenella* in the Southwest Atlantic (Falkland Current), which is consistent with previously detected PST profiles in the area.

The purpose of the main cruise M179/2 FjordFlux was to describe flux dynamics of organic matter (OM) in the Patagonian Cold Estuarine System (PCES) under melt conditions to understand ecosystem functioning. The region, still considered as “pristine”, is under increasing climate change and anthropogenic pressure. FjordFlux aimed to obtain spatial information on the current environmental state by combining results from physical hydrography (e. g., patterns of coastal runoff) and chemistry to reveal terrestrial and marine sources of nutrients, OM, freshwater, and the distribution of greenhouse gases of the PCES. The effect of local flux patterns on planktonic and benthic community composition and functionality was surveyed in fjords that differed in their state of deglaciation (Parry Bay and Garibaldi Sound with sea-terminating glaciers versus Fitton Bay and Gabriel Channel with land-terminating glaciers) and eutrophication, as well as in adjacent areas. FjordFlux followed 26 years after the Victor Hensen Magellan-BC cruise, serving as baseline to detect the state of change. Furthermore, the results support the initiative to establish marine and terrestrial long-term observations in the Beagle Channel (BC).

Specifically, standard CTD profiles were performed, supplemented by a flow-through sensor system (FerryBox) providing high-resolution information on conductivity, temperature, turbidity, chlorophyll-a fluorescence, organic matter fluorescence, and dissolved oxygen in the surface water layer. Apparent optical properties were determined vertically using a free falling hyperspectral light profiler. For horizontal coverage, two sets of three surface radiometers provided high-resolution data on water color, which is related to optically active substances (chl-a, CDOM, and non-algal particles). Vertical profiles of inherent optical properties (IOPs) and organic matter fluorescence were measured in situ at cruise stations, as well as in discrete water samples in the onboard laboratory. Furthermore, particles were also characterized via microscopic imaging. The hydrographical measurements confirmed published data with respect to the main features in the Beagle Channel (e. g. water mass changes with respect to basins and sills, respectively). Furthermore, in both the hydrographical and the optical data, the input of the glacial meltwater into the fjord system of the Beagle Channel could be traced in various locations. Especially the meltwater was characterized as freshwater transporting a large number of inorganic particles, which formed a turbid layer on top of the saltier water in the fjords. This layer had a major impact on light availability in the water column.

Nitrous oxide (N_2O) and methane (CH_4) that are powerful greenhouse gases (GHG) in the atmosphere, with global warming potentials 25 and 298 times greater than carbon dioxide (CO_2), respectively, were measured continuously and subsequently in discrete seawater samples using headspace gas chromatography. Preliminary methane data suggest that there is an imbalance between the ocean and the atmosphere in fjords that end in glaciers, with methane supersaturation in surface waters, which means emissions to the atmosphere. In addition, steep methane gradients were detected throughout the water column.

Geochemical parameters such as nutrients, PON/POC, DOC/DON, and DOM were taken at all stations. The marine macronutrients nitrate, phosphate, and silicate were determined in the euphotic zone (0–40 m depth) in the northernmost and shallowest part of the cruise transect. In the southern, deeper part of the transect, the marine macronutrients nitrate, phosphate, and silicate were determined from the surface to a depth of 100 m. At a depth of 10 m, in addition to the macronutrients mentioned above, nitrite and ammonium were also determined. There was a notable increase in silicate and, in particular, nitrite around the Brecknock Peninsula at intermediate salinities, probably due to the influence of low-salinity waters from the southwestern Pacific. Interestingly, similar high nitrite values have been observed previously in the eastern coastal region of Magallanes. The DOC concentration at a depth of 10 m was estimated using optical properties. A general increase in DOC was observed from east to west, associated with an inverse trend in salinity. This trend was supported by individual cases. For example, in the BC, local increases in salinity were associated with significant

decreases in DOM, and in the fjords, the lowest salinities and highest DOM values were observed. This, together with the lowest DOM values in the Yaghan/Scotia Basin, strongly suggests a primarily terrestrial origin of DOM in this area.

The BC was characterized by high values of ammonium and Chl-a at intermediate salinities. Current data may extend this trend to Garibaldi Sound, the Brecknock Peninsula, and Fitton Bay. In contrast, low ammonium and Chl-a values were observed in the Strait of Magellan (SM) and the Yaghan/Scotia Basin, suggesting a low contribution from these areas to the channel and fjord system of the Magellan region.

High-resolution data on the plankton community and phycotoxins produced by Harmful Algal Bloom (HAB) species collected by phytoplankton net tows revealed high diversity of potentially toxigenic HAB taxa (*Pseudo-nitzschia* cf. *australis*; *P. cf. pseudo-delicatissima*; *PN=Pseudo-nitzschia* spp.; *Alexandrium catenella*; *A. ostenfeldii*; *Azadinium* spp.; *Dinophysis acuminata*; *D. infundibulum*; *D. truncata*; *Dinophysis* spp.; *Gonyulax spinifera*; *Lingulaulax polyedra*; *Protoceratium reticulatum*) and associated phycotoxins (domoic acid, paralytic shellfish poisoning toxins (PSTs), spirolides, dinophysistoxin-1, pectenotoxins, and yessotoxins. It is noteworthy that *A. catenella* and PSTs were restricted to the BC area, but absent in the SM. Furthermore, an unexpectedly dense bloom of *A. catenella* and up to 700 µg PSTs per net tow were detected in Garibaldi Sound, a cold-water fjord with a sea-terminating glacier. The distribution of yessotoxin profiles indicated the presence of *P. reticulatum* in the SM region and of *L. polyedra* in the BC. These findings were confirmed by the analysis of dinoflagellate resting stages (cysts) obtained by multi corer casts that showed the presence of *P. reticulatum* cysts in the SM region and *L. polyedra* cysts in the BC.

Additionally, field samples were collected with Niskin bottles on a rosette at different depths of the euphotic zone to quantify key planktonic taxa, bacteria, the composition of the microbial community through metagenomics, and dissolved vitamin B12. This is the first B12 values for the SM and BC regions with vitamin B12 concentrations being higher than in other oceans, ranging from 0.6 to 4.9 picomoles per liter of water. The highest values were found in semi-enclosed water bodies such as the BC and the fjords, probably due to high terrestrial input and high bacterial abundance. In contrast, in open waters such as the Drake Passage, vitamin B12 concentrations were the lowest.

In addition, the abundance, biomass, viability, elemental and fatty acid composition of meso- and macrozooplankton in the PCES were studied. Along the ship's trajectory, macrozooplankton biomass was estimated using an onboard multibeam echo sounder, which will be validated with data from plankton surveys. In addition, zooplankton respiration, predation, fecal production, and egg production rates were assessed on board. The structure of the benthic community

and its functional biodiversity were assessed in fjord habitats influenced by meltwater. Macrobenthic infauna was collected along the longitudinal axis of selected fjords and adjacent areas, especially at historical stations sampled during the Victor Hensen Magellan expedition. Four replicate samples per station were taken with a large corer (GBC). The material was sieved and fixed. Following the cruise, benthic specimens are being sorted, identified to the lowest possible taxonomic level, and counted. The FjordFlux cruise provided a unique opportunity to calibrate the 26-year-old sediment layer eDNA record with the species sampled at that time during the Victor Hensen Magellan expedition. Finally, a second calibration of the eDNA found in the uppermost sediment layer with the identified present fauna is being carried out. Macrobenthic epifauna and their habitat were recorded using an innovative towed camera platform that integrates an additional acoustic device: the Remotely Operated Vehicle Ocean Bottom Observation System (ROVOS). ROVOS was deployed at PCES stations, including original sampling stations from the RV Victor Hensen expedition. Image analysis is performed on still images to analyze the epibenthic community and calculate diversity, and to compare the results with those from 26 years ago.

Scientific Output

Data

Master Track of Meteor cruise:

<https://doi.pangaea.de/10.1594/PANGAEA.947332>

Multibeam bathymetry raw data:

<https://doi.pangaea.de/10.1594/PANGAEA.952408>

Master tracks in different resolutions, Punta Arenas – Montevideo,
2022-01-19–2022-02-20:

<https://doi.pangaea.de/10.1594/PANGAEA.947333>

ADCP current measurements (38 kHz):

<https://doi.pangaea.de/10.1594/PANGAEA.953100>

Continuous thermosalinograph oceanography:

<https://doi.pangaea.de/10.1594/PANGAEA.951261>

Physical oceanography (CTD):

<https://doi.pangaea.de/10.1594/PANGAEA.960961>

Vertical profiles of nitrous oxide, methane and nutrients:

<https://doi.pangaea.de/10.1594/PANGAEA.971359>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 10–9 in the Seno Almirantazgo/Isla Alta (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946669>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 22–13 of RV Meteor cruise M179/2 in the Boca del Fiordo Garibaldi (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946678>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 13–8 in the Bahía Ainsworth Sur (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946670>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 18–10 in the Canal Ballenero/Bahía Escape (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946674>

Video footage of the benthos and accompanying oceanographic CTD data recorded along 19 ROVOS transects near the Strait of Magellan, the Beagle Channel and Cape Horn (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946688>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 41–12 in the Boca de la Bahía Yendegaia (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946682>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 42–9 in the Canal Beagle (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946683>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 44–11 in the Fiordo Garibaldi Sur (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946685>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 15–9 in the Canal Magdalena (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946672>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 21–9 in the Canal Beagle (Brazo Noroeste) (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946677>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 17–9 in the Canal Magdalena/Isla Meteoro (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946673>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 23–8 in the Canal Beagle/Fiordo Garibaldi (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946679>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 37–10 in the Paso Goree (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946680>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 14–8 in the Bahía Ainsworth Norte (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946671>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 38–11 of the Bahía Oglander (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946681>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 20–10 in the Canal Beagle/Fiordo Poa (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946676>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 49–8 in the Canal Ballenero/Isla Burnt (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946687>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 43–10 in the Canal Beagle (Brazo Noroeste) (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946684>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 19–10 in the Canal Ballenero/Puerto Engaño

(Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946675>

Video footage of the benthos and accompanying oceanographic CTD data recorded along a transect at station 46-12 in the Fiordo Garibaldi Norte (Tierra del Fuego, Chile):

<https://doi.pangaea.de/10.1594/PANGAEA.946631>

Cruise Reports

M179/1: https://doi.org/10.48433/cr_m179_1

M179/2: https://doi.org/10.48433/cr_m179_2

M180 and M188

Quasi-synoptic observations of energy transfer and turbulence in the ocean: First results of the SONETT experiment

Authors

University of Bremen | Bremen, Germany

M. Walter, C. Mertens, R. Oelerich, S. Meethale Puthukkottu

University of Hamburg | Hamburg, Germany

A. Griesel, J. Dräger-Dietel

Hereon Helmholtz Centre | Geesthacht, Germany

J. Carpenter, M. Miracca Lage

Leibniz Institute for Baltic Sea Research Warnemünde | Warnemünde, Germany

L. Umlauf, G. Boskamp, M. Chouksey

Max Planck Institute for Meteorology | Hamburg, Germany

N. Brüggemann, M. Epke

The SONETT Experiment

The current generation of climate models still feature severe biases as well as energetic inconsistencies generated by energetically inconsistent parameterizations of unresolved processes and the model's numerics (e. g. Weigel et al., 2021). The DFG cooperative research center (CRC) 'Energy Transfers in Atmosphere and Ocean' was established in 2016 to address these shortcomings by developing an improved process understanding, design and implement new parameterizations, and develop new numerical and mathematical tools. Within this framework, the observational program of the SONETT (**S**ynoptic **O**bservations – a **N**ested approach to study **E**nergy **T**ransfer and **T**urbulence in the ocean) expeditions was conceived to obtain a data set to study the interlinked processes in the ocean and foster a holistic assessment of the exchange processes between dynamical regimes on a regional scale in the south east Atlantic. Complementing the field work, a global configuration of the ICON Ocean model with tidal and high frequency wind forcing was set up with a telescoping grid focusing on the observational study area.

The three principal dynamical regimes, both in the atmosphere and in the ocean can be classified as (I) geostrophically balanced motion at the largest space and time scales, (II) internal gravity waves over a wide range of spatial scales, and (III) small-scale turbulence down to the smallest space and time scales. The region south of the Walvis Ridge in the south eastern Atlantic Ocean that was chosen as the site of the SONETT experiment (Figure 1) offers the possibility to observe the exchange between the above regimes at the same time: The Walvis Ridge is a site of strong barotropic to baroclinic energy conversion for the internal tide, forming so-called tide beams that emanate from the ridge into the study site. The south east Atlantic is also a place of strong meso- and submesoscale activity. Eddies are shedded by the retroflection of the Agulhas current, and the resulting Agulhas rings travel into the Atlantic on a northwest trajectory through the Walvis Basin, forming a diverse structure of eddies, fronts, and filaments along their way. The bathymetry in the region is mainly deep sea plains with water depths around 5000 m, with a few seamounts, some of which reach up high enough in the water column to potentially affect eddy translation.

The experimental setup during the two R/V METEOR expeditions M180 (SONETT I, 2022) and M188 (SONETT II, 2023) can be divided into three main parts: Firstly, repeated top-to-bottom time series stations of stratification (CTD), currents (lowered ADCP) and upper ocean turbulence (microstructure) over periods of about 36 hours to capture semidiurnal, diurnal, and inertial signals of tides, energy flux, and wave-eddy interaction. Secondly, upper ocean observations of submesoscale variability and mixing, with towed and underway measurements of turbulence, stratification, and flow field. Thirdly, autonomous observations using glider equipped with microstructure probes, and surface drifter release experiments. Also part of the SONETT experiment was a mooring array consisting of two tall moorings and five inverted echo sounders with pressure sensors (PIES) that was deployed during R/V SONNE cruise SO283 (2021) and recovered during M188.

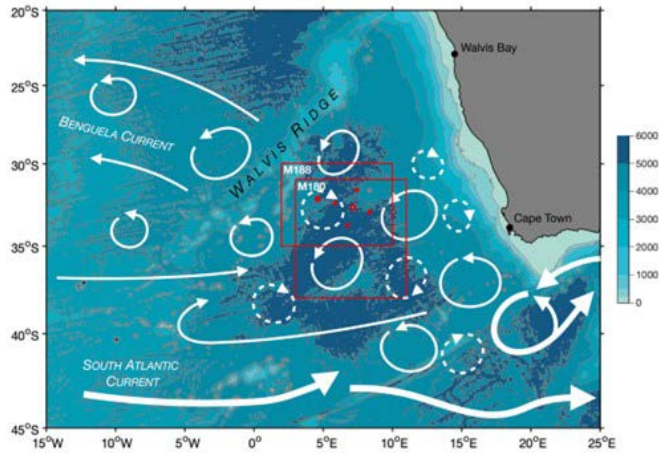


Figure 1: Schematic circulation in the southeastern South Atlantic with Agulhas rings (counter clockwise) generated in the Agulhas retroflection which translate northwestward and cyclonic eddies (clockwise) that translate southeastward (adapted from Richardson (2007)). Indicated are the respective research areas of the Meteor cruises M180 and M188 (boxes) and the position of the mooring array (red circles).

Selected Results

The mooring array was designed to provide time series of the scattering and refraction of the internal tide in the Cape Basin due to interaction with the eddy field. The two moorings were located at depths of about 5000 m and equipped with current meters, ADCPs, and temperature/salinity recorders. They were deployed along the estimated propagation pathway of the energetic internal tides emanating from Walvis Ridge. The first mooring was positioned approx. 200 km to the east of Walvis Ridge to provide a baseline for the energy flux that leaves the generation site, the second mooring about two internal tide mode-one wavelengths (about 280 km) east of the first mooring. The PIES were deployed in an array around the eastern mooring to measure bottom pressure and acoustic round-trip travel time in the overlying water column. The combination of bottom pressure and acoustic travel time allows the calculation of the potential energy of mode one internal waves.

Data from this array (in the form of kinetic energy from the current meter moorings and sea surface height from the PIES instruments) was used to validate the performance of the telescoping ICON Ocean setup in the working area. A comparison between several model configurations (Figure 2) shows that ICON-SMT-Wave demonstrates a remarkable agreement with observations across all evaluations, although limitations due to instrument noise in the observational data prevented a full evaluation across all scales (Epke and Brüggemann, in prep).

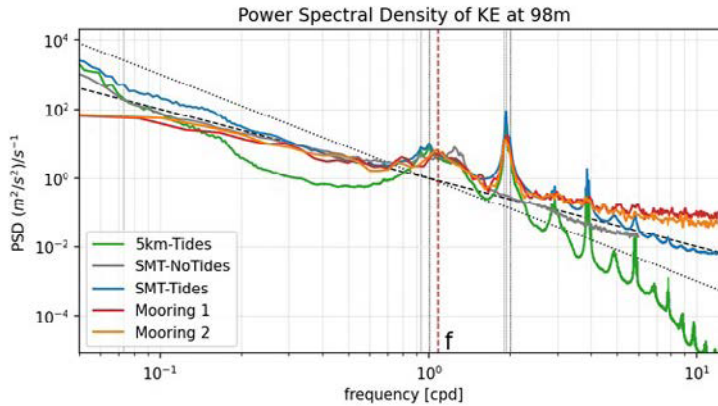


Figure 2: Comparison between the kinetic energy spectra (at 98m depth) from different ICON configurations and the mooring array. The red dashed line denotes the Coriolis frequency f , the grey dotted lines denote the major tidal constituents. (Figure from Epke & Brüggemann, 2025, in prep.)

The horizontal energy flux direction of the stationary M_2 tide at both mooring sites indicates the Walvis Ridge as the common generation source, and the total energy flux at both sites is dominated by non-stationary internal tides. Both stationary and non-stationary tidal fluxes exhibit strong local temporal variability suggesting strong modulation by the Agulhas Rings and other mesoscale variability in the region (Meethale Puthukkottu et al., in prep).

Upper ocean turbulence observations were carried out with ship-based transects and autonomous gliders. The analysis of the shipbased microstructure transects with varying buoyancy fluxes confirmed that net buoyancy flux plays a critical role in determining the stability and mixing rates of submesoscale mixed layer density fronts. Sharp fronts with temperature differences of approximately 0.5°C across a remarkably small lateral scale of order 10 m were observed. These fronts were formed at the leading edge of a buoyant gravity current of 20 m to 40 m thickness that propagated at a speed of order 0.1 m s^{-1} relative to the colder and thus denser surrounding waters. High-resolution turbulence microstructure observations revealed strongly enhanced turbulence inside the nose of the gravity current, while turbulence in the trailing bulk region was mainly wind- and convectively-driven and showed a strong diurnal modulation. Satellite and meteorological data suggest that the gravity current was triggered by the mesoscale strain-induced sharpening and final collapse of a larger-scale front at the edge of a mesoscale eddy during a period with decaying winds. In contrast to previous studies that have identified similar buoyant gravity currents in the equatorial ocean, our data suggest that they can also form at a mid-latitude location where rotational effects are strong. This suggests that even balanced fronts can decay into gravity currents under certain conditions, indicating a potentially important pathway for mesoscale energy dissipation and mixing (Boskamp et al., in prep).

The gliders were equipped with microstructure sensors measuring shear and temperature and were deployed to target specific oceanographic features such as fronts and eddies by continuously profiling the upper 100 m and 1000 m of the water column. The shallow (100 m) glider was configured to sample all the way to the surface, allowing it to capture near-surface turbulence and thermal structure during the upcasts. Turbulent entrainment of momentum from below the Diurnal Warm Layer was found to be important in the evolution of surface currents. The upper ocean potential energy budget was dominated by the incoming solar radiation, with only a small contribution from turbulent mixing. Turbulent shear production, however, was found to be an important influence on the upper ocean mean kinetic energy, receiving a similar fraction of the wind work as the acceleration of the diurnal jet (Miracca Lage et al., 2025).

During the glider deployments during the two campaigns, two types of Agulhas Rings (surface- and subsurface-intensified) were covered by the deep (1000 m) glider, highlighting their distinct characteristics. Our analysis reveals that major differences between the two eddy types occur near the eddy centre, where the subsurface-intensified Agulhas Ring exhibits elevated energy dissipation and diapycnal mixing beneath the surface mixed layer. Shear-induced Kelvin-Helmholtz instability is identified as a significant contributor to the diapycnal mixing at the rim of the anticyclonic eddy, while the expansion of the thermocline within the eddy is responsible for the highest energy dissipation and mixing rate within the eddy centre. The mixing processes within the eddy are strongly modulated by local forcing such as wind and tides; notably in conditions of moderate wind and spring tide, the tidal cycle exerts a considerable influence on the development of low and high stratification. Further analysis shows that mixing length scales are also elevated within the sub-surface intensified eddy, suggesting enhanced vertical and lateral transport of ocean properties (Oelerich et al., in prep).

Current-following surface drifters were deployed in a hierarchical fashion to span a range of initial separations between the drifters, thereby resolving the small-scale dispersion regime. Two different kinds of drifters floating directly at the surface (50 cm) and in the mixed layer (15 m) were released in near-simultaneous deployments in the working area. The characteristics of turbulence and processes driving it in the regime connecting mesoscales (upscale energy transfer) and classical microscale turbulence (downscale energy transfer) have been analysed utilizing two-point velocity data from the drifter release experiments. For the mixed layer drifter, the compensated third order longitudinal velocity structure function shows a positive plateau for inertial scales roughly between 15 km and 150 km, indicative of an inverse energy cascade. In contrast, the surface drifter do not show a positive plateau at these scales, but instead evidence of a forward cascade (negative plateau) and Kolmogorov self-similarity on a spatial scale of 500 m (Draeger-Dietel et al., in prep).

Reference

Weigel K, Bock L, Gier BK, Lauer A, et al., Earth System Model Evaluation Tool (ESMValTool) v2.0–diagnostics for extreme events, regional and impact evaluation, and analysis of Earth system models in CMIP, *Geosci. Mod. Devel.* 2021, 14(6), 3159–3184.

Scientific Output

List of Publications

Aravind A, Griesel A, Draeger-Dietel J & Breunig E, The vertical dependence of the eddy diffusivity tensor in the mixed layer in the South Atlantic, 2025, in preparation for submission.

Chouksey M, Eddy-tide interactions and energy exchanges in the South Atlantic Ocean, 2025, in preparation for submission.

Draeger-Dietel J, Griesel A, Breunig E, Carrasco Alvarez R & Horstmann J, Vertical dependence of pair dispersion regimes from drifter observations in the South Atlantic, 2025, in preparation for submission.

Draeger-Dietel J, Griesel A, Breunig E, Carrasco Alvarez R & Horstmann J, An assessment of structure functions to estimate energy transfers in the South Atlantic from surface drifters, 2025 in preparation for submission.

Epke M & Brüggemann N, Impact of tides and eddies on ocean energy spectra in a submesoscale resolving simulations of the South Atlantic, 2025, in preparation for submission.

Epke M & Brüggemann N, High-frequency variability generated by mesoscale eddies interacting with bathymetry in a submesoscale-resolving simulation of the South Atlantic, 2025, in preparation for submission.

Miracca-Lage M, Ménesguen C, Schmitt M, Umlauf L, Merckelbach L & Carpenter JR, Turbulence observations and energetics of Diurnal Warm Layers, *Journal of Physical Oceanography* 2025, doi:10.1175/JPO-D-25-0026.1.

Meethale Puthukkottu S, Mertens C, Walter M & Rhein M, Observation of coherent and incoherent internal tide energy flux in Walvis Bay, south Atlantic, 2025, in preparation for submission.

Oelerich R, Walter M, Wu K-Y & Bachmayer R, Energy dissipation and mixing within surface- and sub-surface intensified Agulhas Rings, 2025, in preparation for submission.

Theses:

Aravind A, The eddy diffusivity tensor in the mixed layer in the South Atlantic: surface vs 15m depth, MSc thesis 2025, Univ. Hamburg (in progress).

Boskamp G, Frontal dynamics and mixing in the region of the Agulhas Ring pathway, MSc thesis 2024, Univ. Rostock.

Epke M, Kilometer-scale ocean turbulence and waves in the North and South Atlantic, PhD Thesis 2025, Univ. Hamburg, doi:10.17617/2.3658361.

Miracca Lage, M, Turbulence variability and energy pathways in the surface mixed layer, PhD Thesis 2024, Univ. Hamburg, doi:10.1029/2023GL107336.

Roscelli L, Upper-ocean turbulence and mixing in the southern Atlantic, MSc thesis 2023, Univ. Bremen.

Wu K-Y, Energy dissipation within an anti-cyclonic eddy in the South Atlantic, MSc thesis 2024, Univ. Bremen/Erasmus Mundus.

List of conference presentations

2022 | **Upper-ocean mixing from shear microstructure and density** EGU General Assembly, Vienna, Austria.

2022 | **Wave-eddy interactions in the South Atlantic** FilaChange 2022, An international conference on ocean processes linking filaments and finescales (1–100 km) with climate change, Paris, France.

2023 | **Evidence of a dual kinetic energy cascade by surface drifter observation in the Walvis Ridge region** EGU General Assembly, Vienna, Austria.

2023 | **From observations to 1D-models: how can we improve the parameterizations of mixed-layer turbulence?** 13th International Workshop on Modeling the Ocean, Hamburg, Germany.

2023 | Evidence of a dual kinetic energy cascade by surface drifter observation in the Walvis Ridge region Eddy-Wave Meeting, Hamburg, Germany.

2024 | Evolution from Agulhas ring to mode-water eddy? EGU General Assembly, Vienna, Austria.

2024 | Impact of tides and eddies on ocean energy spectra in submesoscale resolving simulations of the South Atlantic EGU General Assembly, Vienna, Austria.

2024 | Buoyant gravity currents triggered by a collapsing mid-latitude submesoscale front EGU General Assembly, Vienna, Austria.

2024 | The evolution of turbulence, stratification, and the surface jet in Diurnal Warm Layers EGU General Assembly, Vienna, Austria.

2024 | Dual energy cascade in ocean macroscopic turbulence: Kolmogorov self-similarity in surface drifter observations and Richardson-Obukhov constant DPG spring meeting, Berlin, Germany.

2024 | Buoyant gravity currents triggered by a collapsing midlatitude submesoscale front Ocean Mixing Gordon Research Conference, South Hadley, Massachusetts, United States.

2024 | Impact of tides and eddies on ocean energy spectra in submesoscale resolving simulations of the South Atlantic TAPGFD (Theoretical and Practical Perspectives in Geophysical Fluid Dynamics), ICTS Bangalore, India.

2025 | Observation of coherent and incoherent internal tide energy flux in Walvis Bay, south Atlantic OSICON-25, Goa, India.

2025 | Energy dissipation and mixing within surface- and sub-surface intensified Agulhas Rings EGU General Assembly, Vienna, Austria.

2025 | Impact of mesoscale eddies and bathymetry on high-frequency ocean dynamics in a submesoscale resolving simulation of the South Atlantic EGU General Assembly, Vienna, Austria.

2025 | Shear instability of the ocean's Diurnal Warm Layer EGU General Assembly, Vienna, Austria.

2025 | Turbulence observations and energetics of Diurnal Warm Layers EGU General Assembly, Vienna, Austria.

2025 | **Investigating vertical dependence of turbulence regimes and lateral mixing in the mixed layer from drifter observations in the South Atlantic** EGU General Assembly, Vienna, Austria.

2026 | **Thermohaline intrusions, diurnal warm layers and turbulence: observations of a high-strain mesoscale eddy field** AGU Ocean Sciences Meeting, Glasgow, UK. (submitted)

2026 | **Adaptive sampling strategies with ocean gliders** AGU Ocean Sciences Meeting, Glasgow, UK. (submitted)

Data

Master track M180:

<https://doi.org/10.1594/PANGAEA.947601>

<https://doi.org/10.1594/PANGAEA.947603>

Multibeam bathymetry M180:

<https://doi.org/10.1594/PANGAEA.965773>

Multibeam water column M180:

<https://doi.org/10.1594/PANGAEA.965774>

Thermosalinograph M180:

<https://doi.org/10.1594/PANGAEA.959031>

Physical oceanography (CTD) M180:

<https://doi.pangaea.de/10.1594/PANGAEA.982252>

Surface drifter dataset M180:

<https://doi.pangaea.de/10.1594/PANGAEA.955925>

Master track M188:

<https://doi.org/10.1594/PANGAEA.962738>

<https://doi.org/10.1594/PANGAEA.962739>

Vessel mounted ADCP current measurements (75 kHz) M188:

<https://doi.org/10.1594/PANGAEA.983495>

Vessel mounted ADCP current measurements (38 kHz) M188:

<https://doi.org/10.1594/PANGAEA.983547>

Thermosalinograph M188:

<https://doi.org/10.1594/PANGAEA.968986>

Lowered ADCP current measurements M188:

<https://doi.pangaea.de/10.1594/PANGAEA.982252>

Surface Drifter Data M188:

<https://doi.org/10.1594/PANGAEA.968619>

Processed data for “Turbulence Observations and Energetics of Diurnal Warm Layers”:

<https://doi.org/10.5281/zenodo.1465481>

Cruise Reports

M180: https://doi.org/10.48433/cr_m180

M188: https://doi.org/10.48433/cr_m188

Trans-Atlantic Equatorial cruise II

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

P. Brandt, M. Körner, A. C. Hans, R. A. Imbol Kounoue, M. Dengler, C. McKellar,
R. Kiko

The Transatlantic Equatorial Cruise II (TRATLEQ II) was an interdisciplinary cruise focusing on upwelling in the tropical Atlantic. The main topics included the physical forcing of upwelling, its importance for biological production and plankton communities, associated chemical cycles, and the current system that sets the background conditions for downward carbon export. TRATLEQ II was the second cruise to extend across the entire equatorial section from the eastern to the western boundary (Figure 1). In contrast to the first cruise (TRATLEQ I, M158, Sep./Oct. 2019), which took place shortly after the peak of equatorial upwelling, TRATLEQ II was designed to cover the period prior to the onset of enhanced equatorial upwelling. TRATLEQ II contributed to the GEOMAR research program OCEANS, the EU project TRIATLAS, the “Make Our Planet Great Again” project led by R. Kiko, and the BMBF cooperative project BANINO.

Key results from the equatorial measurements include the identification of three independent wind-driven processes that control the seasonal cycle of equatorial productivity (Brandt et al., 2025). Particularly important was the timing of the two Transatlantic transects during boreal spring and autumn. With these two cruises, it could be clearly shown that the core of the Equatorial Undercurrent (EUC) and the nitracline shoal and deepen independently.

The three wind-driven processes are:

1. The shoaling and deepening of the nitracline in the eastern and western equatorial Atlantic, respectively, in response to strengthening easterly winds, and vice versa during weakening winds.
2. The shoaling and deepening of the eastward velocity core caused by the superposition of the EUC and resonant equatorial waves of annual period.

3. Enhanced turbulence in the shear zone above the eastward velocity core, associated with deep-cycle turbulence (Figure 1).

The combination of these three processes results in an unproductive period during boreal spring, characterized by a shallow eastward velocity core and a deep nitracline, and peak productivity during boreal summer, when the nitracline is shallowest and the eastward velocity core is deepening.

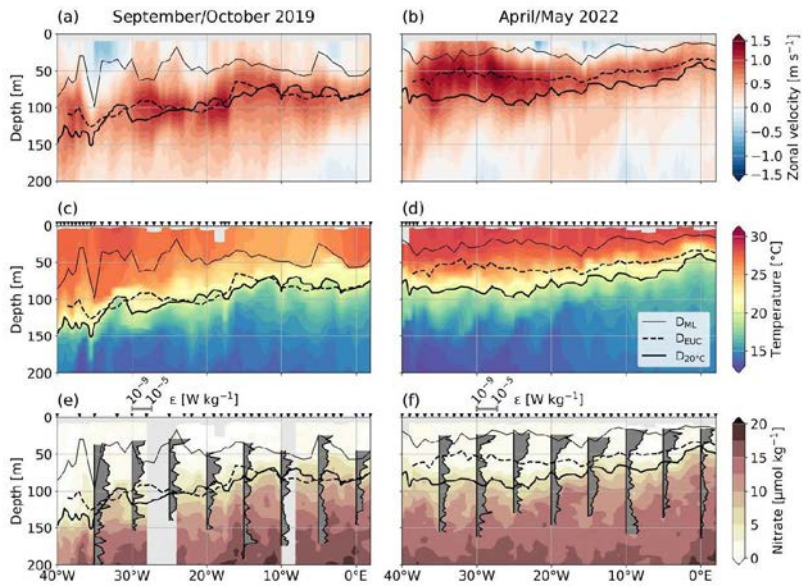


Figure 1: Velocity, temperature, nitrate and mixing during two trans-Atlantic crossings. Shown are zonal velocity (a,b), temperature (c,d) and nitrate (e,f) taken during R/V Meteor cruises M158 from 29 September to 22 October 2019 (a,c,e) and M181 from 30 April to 20 May 2022 (b,d,f). The mixed layer depth, DML, is marked by thin solid lines, the EUC core depth, DEUC, by thick dashed lines and the depth of the 20 °C isotherm, D20°C, as a proxy for the nitracline by thick solid lines. Also included in e and f are mean profiles of the turbulence dissipation rate, ϵ (grey-filled areas; vertical black lines mark $10^{-9} \text{ W kg}^{-1}$; scale at the top of the panels). Black triangles at the top of c and d and e and f mark locations of CTD and microstructure stations, respectively. From Brandt et al. (2025).

TRATLEQ1 & 2 also aimed to investigate how surface productivity and carbon export are related. To investigate this question, high-resolution particle size distribution data from Underwater Vision Profilers (UVP5) were analyzed. During the productive fall season, upwelling and tropical instability waves enhanced local primary production and supported the deep export of large, fast-sinking aggregates. During the low productivity boreal spring, we observed unexpectedly high concentrations of small particles (0.1–0.5 mm) in the central basin, concentrated within the Equatorial Undercurrent (EUC), which is supplied by the North Brazil Current retroflexion. Backward trajectory analysis, and biological and hydrographic evidence suggest that these particles originate from the South

American continental margin and are laterally transported eastward, due to a combination of shelf resuspension by energetic currents and tides, and a short pathway from the shelf to the EUC. During the low-productivity period, between 15–35°W, over 70% of the POC flux in the upper 200 m might be attributed to small particles (0.05–0.5mm) carried within the EUC. These results challenge the assumption that carbon export in the Equatorial Atlantic is tightly coupled to local primary production and reveal that the EUC plays a key role in subsurface carbon redistribution during the unproductive period.

Both Transatlantic transects were used to characterize the diurnal cycle of the near-surface ocean (Hans et al., 2024). Using different types of surface drifters, marine radar, and shipboard ADCP data, the diurnal cycle of the velocity difference between the surface and 15 m depth could be determined (Figure 2). This velocity difference, which reaches a maximum in the afternoon, reveals the existence of a diurnal surface jet. The maximum shear velocity and stratification, located below the surface jet, deepen during the day, inducing nighttime deep-cycle turbulence in the permanent shear layer above the eastward velocity core.

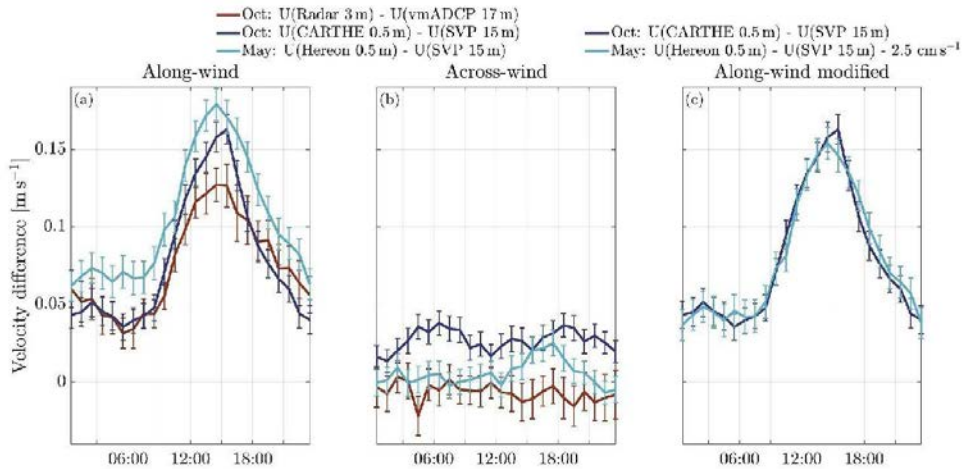


Figure 2: Mean diurnal cycles of vertical differences of horizontal velocities in (a) along- and (b) across-wind direction as a function of local solar time. The velocity differences are obtained from the marine radar and the uppermost bin of the vessel mounted ADCP during M158 (dark red) and from the M158 (dark blue) and M181 (light blue) drifter experiments. Further, (c) compares the drifter experiments in (a) with a background velocity difference of 2.5 cm s⁻¹ removed for M181. The error bars represent the standard error. From Hans et al. (2024).

During M181, the deep equatorial circulation was also studied. Both Transatlantic transects show the presence of equatorial deep jets, strongest at depths between 500 and 2000 m. Since the two transects were about 2.5 years apart, and the oscillation period of equatorial deep jets in the Atlantic is about 4.5 years, the difference between the two velocity fields reveals a coherent velocity signal of

higher baroclinic modes, with eastward and westward jets showing a downward tilt from west to east (Figure 3). These basin-wide structures indicate a basin resonance associated with high-baroclinic mode equatorial Kelvin and Rossby waves (McKellar, 2025).

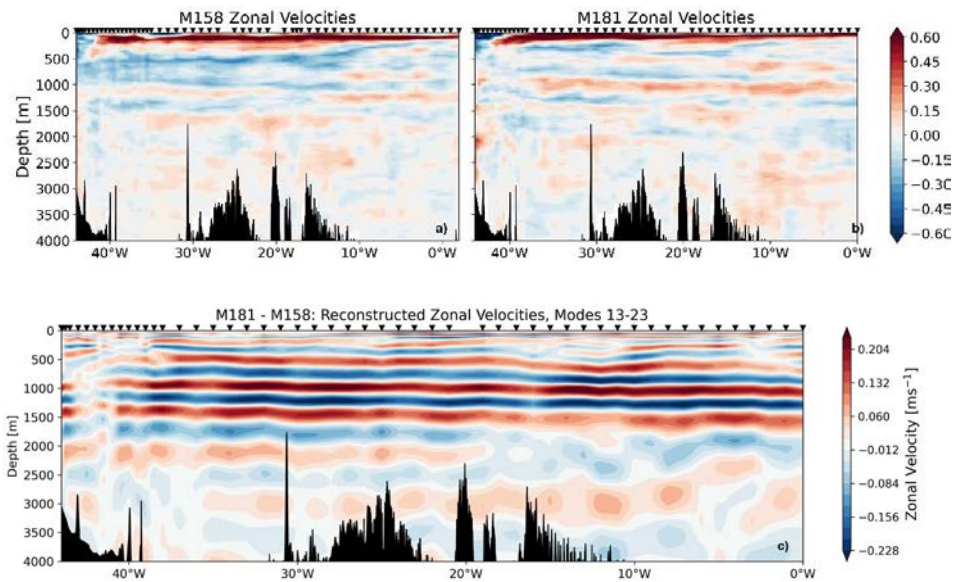


Figure 3: Zonal velocity during two trans-Atlantic crossings (upper panels), taken during R/V Meteor cruises M158 and M181 and zonal velocity difference between both cruise (lower panel). The zonal velocity difference is calculated by reconstructing the velocity fields using only higher baroclinic modes (modes 13–23). From McKellar (2025).

Besides the equatorial Atlantic, another study area was the coastal upwelling region off Angola, where the same techniques were applied to better understand the functioning of this tropical upwelling system. A particular focus was on the export flux of carbon to mesopelagic and bathypelagic depths, associated with particle flux and diel vertical zooplankton migration.

Physical ocean dynamics were investigated through hydrographic, current, and microstructure measurements. These were designed to improve our understanding of upper-ocean mixing processes and to quantify ventilation and water mass exchange between the western and eastern boundaries. The measurement program also included servicing the long-term mooring off Angola at 11°S.

Key findings show that productivity in the tropical Angolan upwelling system is driven by a combination of coastal trapped waves originating at the equator and tidal mixing on the shelf, as identified by combining observational results from cruise M181 and previous expeditions (Körner et al., 2024a). By calculating a

mean section of turbulence dissipation rates from all available measurements along 11°S, including M181, and by accounting for seasonal variations in nitrate distributions forced by coastal trapped waves, seasonal variations in the upward nitrate flux at the shelf were revealed (Figure 4), explaining the high productivity during austral winter.

In addition, the mooring time series off Angola was used to investigate the extreme warm event that occurred there in 2021 (Imbol Koungue et al., 2024). Data from a BGC Argo float recovered during the cruise were analyzed to study episodes of downward carbon flux in the tropical Angolan upwelling system (Soviadan et al., 2025).

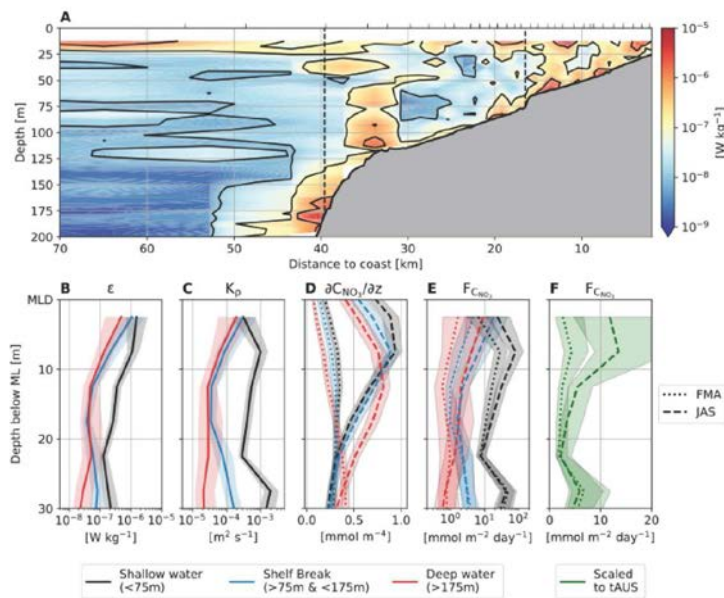


Figure 4: Vertical mixing and diffusive nitrate fluxes in the tropical Angolan upwelling system (tAUS). (A) Mean section of dissipation rate of turbulent kinetic energy (TKE) at 11°S as a function of distance to coast from microstructure data. Microstructure data are binned together into groups of 20 profiles, and the spatial extent of the groups is indicated by vertical ticks at the top of the plot. Measurements within the mixed layer and in the upper 10 m were discarded before averaging. Vertical dashed lines separate the three depth regions. (B to E) Mean profiles taken in shallow water (water depth <75 m, black), in the area of the shelf break (water depth >75 and <175 m, blue), and in deep waters (water depth >175 m, red) as a function of distance to the mixed layer depth. (B) Dissipation rate of TKE ($W kg^{-1}$). (C) Eddy diffusivity ($m^2 s^{-1}$). (D) Vertical nitrate gradient ($mmol m^{-4}$) inferred from oxygen data. (E) Turbulent nitrate flux ($mmol m^{-2} day^{-1}$). (F) Turbulent nitrate flux ($mmol m^{-2} day^{-1}$) scaled to the whole tAUS. [(D) to (F)] Results for February–April (dotted) and July–September (dashed). Shaded areas indicate 95% confidence intervals. Note the logarithmic scale in (B), (C), and (E). From Körner et al. (2024a).

Scientific Output

List of Publications

Brandt P, Alory G, Awo F M, Dengler M, et al., Physical processes and biological productivity in the upwelling regions of the tropical Atlantic, *Ocean Sci.*, 2023,19, 581-601, doi:10.5194/os-19-581-2023.

Brandt P, Körner M, Moum J N, Roch M, et al., Seasonal productivity of the equatorial Atlantic shaped by distinct wind-driven processes, *Nat. Geosci.*, 2025, 18, 84-90, doi:10.1038/s41561-024-01609-9.

Hans AC, Brandt P, Gasparin F, Claus M, et al., Observed diurnal cycles of near-surface shear and stratification in the equatorial Atlantic and their wind dependence, *J. Geophys. Res. Oceans* 2024, 129, e2023JC020870, doi:10.1029/2023JC020870.

Imbol Koungue R A, Brandt P, Prigent A, Costa Aroucha L, et. al., Drivers and impact of the 2021 extreme warm event in the tropical Angolan upwelling system, *Scientific Reports*, 2024, 14, 16824, doi:10.1038/s41598-024-67569-7.

Körner M, Brandt P & Dengler M, Seasonal cycle of sea surface temperature in the tropical Angolan Upwelling System, *Ocean Sci.* 2023, 19, 121-139, doi:10.5194/os-19-121-2023.

Körner M, Brandt P, Illig S, Dengler M, et al., Coastal trapped waves and tidal mixing control primary production in the tropical Angolan upwelling system, *Sci. Adv.*, 2024a, 10, eadj6686, doi:10.1126/sciadv.adj6686.

Körner M, Brandt P & Dengler M, Strength and timing of austral winter Angolan coastal upwelling, *Scientific Reports*, 2024b, 14, 27400, doi:10.1038/s41598-024-77917-2.

Soviadan Y D, M Beck, J Habib, A Baudena, et al., Marine snow morphology drives sinking and attenuation in the ocean interior, *Biogeosciences*, 2025, 22, 3485-3501, doi:10.5194/bg-22-3485-2025.

Ph.D. and Master Theses:

Körner M, Physical drivers of seasonal variability in the tropical Angolan upwelling system, Ph.D. thesis, Christian-Albrechts-Universität zu Kiel, 129 pp., 2024

McKellar C, Zonal velocity variability in the equatorial Atlantic and Pacific Ocean, Master thesis, Christian-Albrechts-Universität zu Kiel, 116 pp., 2025.

Schmidt IL, Phytoplankton community structure in the equatorial Atlantic and its temporal and spatial distribution, Master thesis, Universität Bremen, 70pp., 2023.

List of conference presentations

2025 | **Physical processes and biological productivity in the upwelling regions of the tropical Atlantic**, Pan-CLIVAR Meeting, Bali, Indonesia

2025 | **Seasonal productivity of the equatorial Atlantic shaped by distinct wind-driven processes**, CELLO Conference, Hamburg, Germany

2025 | **Seasonal productivity of the equatorial Atlantic shaped by distinct wind-driven processes**, European Geosciences Union, General Assembly 2025, Vienna, Austria

2025 | **Dynamics and morphology of sinking particles in the equatorial Atlantic during the 2021 Atlantic Nino**, European Geosciences Union, General Assembly 2025, Vienna, Austria

2025 | **Resolving plankton and particle dynamics at local to global scales via pelagic imaging**, Inaugural Lecture R. Kiko, GEOMAR, Kiel, Germany

2024 | **Tropical upwelling systems**, GEOMAR-IOW Workshop, IOW, Warnemünde, Germany

2024 | **Seasonal cycle of mixing and upward nitrate supply in the equatorial Atlantic cold tongue (online)** Laboratoire d'Océanographie de Villefranche-sur-Mer, France.

2024 | **TRATLEQ – primary production and N-fixation (online)** Laboratoire d'Océanographie de Villefranche-sur-Mer, France.

2024 | **TRATLEQ – particle flux from in situ pumps**, Laboratoire d'Océanographie de Villefranche-sur-Mer, France.

2024 | **TRATLEQ – zooplankton and particle dynamics**, Laboratoire d'Océanographie de Villefranche-sur-Mer, France.

2024 | **Role of equatorial basin modes for equatorial Atlantic productivity**, Atmosphere and Ocean Dynamics 2024, Kiel, Germany

2024 | Drivers and impact of the 2021 extreme warm event in the tropical Angolan upwelling system, Ocean Sciences Meeting 2024, New Orleans, USA

2024 | Diazotrophy surprises in the Equatorial Atlantic Ocean: unprecedented nitrogen fixation in the upwelling system. Ocean Sciences Meeting 2024, New Orleans, United States of America

2023 | Particulate carbon export using ^{234}Th - ^{238}U disequilibrium along the Atlantic Equatorial line ASLO Aquatic Sciences Meeting, Palma De Mallorca, Spain

2023 | Modulation of equatorial currents and tropical instability waves during the 2021 Atlantic Niño TRIATLAS Final Conference and General Assembly/PIRATA-26/TAV Meeting, Banyuls-sur-Mer, France

2023 | Seasonal cycle of mixing and upward nutrient supply in the equatorial Atlantic cold tongue TRIATLAS Final Conference and General Assembly/PIRATA-26/TAV Meeting, Banyuls-sur-Mer, France

2023 | Zooplankton diel vertical migrations in the tropical Atlantic and their impact on carbon export and particulate matter distribution, TRIATLAS Final Conference and General Assembly / PIRATA-26/TAV Meeting, Banyuls-sur-Mer, France

2023 | Seasonal cycle of mixing and upward nutrient supply in the equatorial Atlantic cold tongue IUGG/IAPSO, Berlin, Germany

2023 | Diurnal cycle of near-surface shear and stratification in the equatorial Atlantic IUGG/IAPSO, Berlin, Germany

2023 | Upper ocean frontal dynamics in Tropical Instability Waves IUGG/IAPSO, Berlin, Germany

2023 | Modulation of Tropical Instability Waves and chlorophyll concentration by equatorial waves during the 2021 Atlantic Niño EGU General Assembly, Vienna, Austria

2023 | Investigating long-term variability and trends of Atlantic Tropical Instability Waves with multidecadal satellite observations and mooring data US CLIVAR Mesoscale and Frontal-Scale Air-Sea Interactions Workshop, Boulder, USA

2023 | Detecting the ocean response to climate variability: Long-term observatories of RD1 [poster], 12th SAB Meeting, Kiel, Germany.

2023 | **Tropical Ocean Dynamics related to Equatorial Upwelling** Physics of the Ocean Summer School, Bad Honnef, Germany

2022 | **Physical drivers of Southwest African coastal upwelling and its response to climate variability and change** Open Science Conference on Eastern Boundary Upwelling Systems (EBUS), Lima, Peru

2022 | **Investigating long-term changes of equatorial ocean dynamics with 20 years of current velocity observations from a moored observatory at 0°N, 23°W** AGU Fall Meeting, Chicago, USA

2022 | **Multidecadal Intensification of Atlantic Tropical Instability Waves** TRIATLAS 3rd Conference and General Assembly/PIRATA-25/TAV Meeting, Porto de Galinhas, Brazil

2022 | **Seasonal cycle of upwelling and upward nutrient supply in the equatorial Atlantic**, International Conference Themes 2022, Venice, Italy

2022 | **Tropical Ocean Dynamics related to equatorial upwelling and oxygen minimum zones** TRIATLAS Summer School, Recife, Brazil

2022 | **Phytoplankton Biomass and Primary Production in the Equatorial Atlantic – Who, how much, and why?** TRIATLAS Summer School, Recife, Brazil

Data

Physical oceanography (CTD):
<https://doi.pangaea.de/10.1594/PANGAEA.952520>

ADCP current measurements (38 and 75 kHz):
<https://doi.pangaea.de/10.1594/PANGAEA.956143>

Microstructure data:
<https://doi.pangaea.de/10.1594/PANGAEA.953873>

Continuous thermosalinograph oceanography:
<https://doi.pangaea.de/10.1594/PANGAEA.958394>

Physical oceanography from mooring KPO_1235:
<https://doi.pangaea.de/10.1594/PANGAEA.962193>

Hereon Surface Drifter Data of the Equatorial Atlantic:
<https://doi.org/10.1594/PANGAEA.955925>

Data product of full-depth current velocity observations at 0°N, 23°W from 2001–2021 (v2.0):

<https://doi.pangaea.de/10.1594/PANGAEA.963935>

PlanktoScope v2.1 image set 1:

<https://ecotaxa.obs-vlfr.fr/prj/14862>

Cruise Report

M181: https://doi.org/10.48433/cr_m181

M182

Role of Eddies in the Carbon Pump of Eastern Boundary Upwelling Systems, REEBUS | 01.06.–10.07.2021 | Results from cruise M182

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

M. Keller, J. Greinert, A. W. Dale, H.J. Hoving, B. Pontiller, D. Schappukat,
S. Sommer, E. Wenzlaff

Introduction

The research cruise M182 (MOSES Eddy-III) concludes a trilogy of research cruises conducted in the frame of the Helmholtz Association's Modular Observation Solutions for Earth Systems (MOSES) infrastructure, aiming at a comprehensive multi- and interdisciplinary study of ocean eddies in the northern tropical Atlantic. As an integral part of the BMBF-funded project "Role of eddies in the carbon pump of eastern upwelling systems – Demonstration Case Canary Current System" (REEBUS), launched in 2019, this study focuses on investigating the multi-layered influence of eddies on the lateral transport of biogeochemical properties and the carbon pump within deep-sea ecosystems. Ocean eddies have a significant impact on the physical, biogeochemical and biological aspects of coastal upwelling regions. Given the profound socio-economic impact of coastal upwelling areas, REEBUS takes a multidisciplinary approach to investigate the influence of ocean eddies on these systems. This expedition is motivated by the objective of acquiring novel insights into the functional dynamics of eddies, specifically elucidating their role in the CO₂ source and sink functions inherent to eastern boundary upwelling systems. Furthermore, our investigative efforts encompassed a thorough examination of the biological carbon pump within both the designated upwelling areas and their associated oligotrophic regions. The synthesis of data from all REEBUS cruises, coupled with the inclusion of data from prior expeditions (MOSES Eddy-I and II) within this geographical region, promises to yield a high scientific potential.

Overarching Objectives

Cruise M182 is the third and last research cruise within the frame of the BMBF funded REEBUS project with the overarching objective of studying regional eddies in eastern boundary upwelling systems, their impact on pelagic biogeochemical processes and the modulation of the carbon export towards the seafloor. In parallel, it is part of the Helmholtz funded technology project MOSES that aimed to develop modular systems for Earth System studies. Both projects jointly conducted the previous two RV METEOR cruises M156 and M160. The study area of the REEBUS project is the northern tropical Atlantic between Cabo Verde and Mauritania along an E-W transect at about 18° north. The two previous cruises focused on water column investigations including eddy hunting by using physical oceanography tools and approaches (ship based ADCPs, CTD, glider) with parallel water column sampling for biogeochemical investigations. In addition, seafloor studies with sediment sampling, optical and acoustic mapping as well as in-situ biogeochemical flux measurements with landers were performed. Furthermore, M160 coordinated a mission with the Stemme S10 VTX motorglider from Aachen University for detecting eddies.

During M182 we focused on biogeochemical investigation of the seafloor but also did a substantial water column sampling program including an ADCP and CTD-based eddy hunt survey. As the time between applying for the cruise and the actual cruise was rather long, an additional group looking at gelatinous organisms in the water column joined and broadened our studies. For achieving our overarching objective, a number of tasks guided the work during M182 which can be summarized as follows:

- Map, characterize and ‘pin-point’ an eddy using physical oceanography (ship-based ADCP, CTD) and satellite-based sea-surface height information
- Sample the eddy along a cross-transect for biogeochemical investigations
- Perform vertical water column sampling and optical investigations along horizontal transects for gelatinous organisms
- Investigate the potentially small scaled heterogeneity of the biogeochemical carbon turnover on the seafloor using o AUV based mapping technologies (acoustically and optically)
- XOFOS-based high resolution optical seafloor mapping
- detailed sediment sampling with TV-MUC and GC
- in-situ biogeochemical flux measurements with BIGO landers and the Panta Rhei rover

- Deploy the BBL lander (CTD, ADCP, sediment trap, time laps camera) and the deep-sea rover Panta Rhei (benthic oxygen flux chambers, ADCP, CTD, cameras) to investigate the potential impact of a passing eddy until their recovery on 15 January 2023 with RV MS MERIAN

Summary of cruises

Since Eddies do form frequently within proximity of the west African coast, but their lifespan and propagation path are difficult to predict, an extensive benthic and pelagic program was launched within the zonal eddy passage situated at 18° latitude before a suitable eddy was identified. It extends from the vicinity of Cabo Verde to the Mauritanian continental shelf (designated as E1-E4). A sequence of benthic stations was designated at varying water depths and in proximity to the continental shelf, serving as locations for systematic sampling. Furthermore, deviating from the initial cruise proposal, the itinerary was expanded to incorporate investigations at the Senghor Seamount and the E1 hill station. When selecting these additional sites, it was considered that seamounts represent unique ecological niches in the surrounding deep-sea environment. In parallel, the water column was sampled through the deployment of a multi-net apparatus. The scientific undertakings commenced with a multinet haul and the deployment of a Conductivity, Temperature, and Depth (CTD) profiler at the Cabo Verde Ocean Observatory site (CVOO), an established long-term monitoring station that undergoes periodic sampling. In each working area, sediment was sampled via TV-MUC and gravity corer for geochemical analysis. The deep-sea rover (DSR) Panta Rhei and the BIGO (Benthic In situ Gravimetric Observatory) lander were deployed with the primary aim of quantifying benthic fluxes over an extended observational period spanning several days. Additionally, the cruise incorporated the use of a towed extended ocean floor observation system (XOFOS), which allows high-resolution visual documentation of the seafloor surface through video profiles. This program enabled the investigation of variabilities in bioturbation patterns, macrofaunal communities, small-scale seafloor heterogeneity, and the intricacies of biogeochemical carbon turnover processes. It was repeated in each research area.

Eventually, one eddy was identified via satellite images and could be sampled in the second week of the cruise. Acquired underway ADCP and CTD data was sent on a regular basis to GEOMAR for parallel analysis, which supported the eddy detection and identification. Additional ADCP surveys crossing the eddy from different directions are needed to identify the eddy core location for sampling to investigate the characteristics and dynamics of oceanic eddies, including their physical properties and potential impact on carbon fluxes. Once the eddy is found, it was sampled along a cross-transect for biogeochemical and microbiological investigations.

Towards the end of the cruise an area needed to be defined, which is well-suited in order to deploy the BBL lander and the Panta Rhei rover for the long-term measurements.

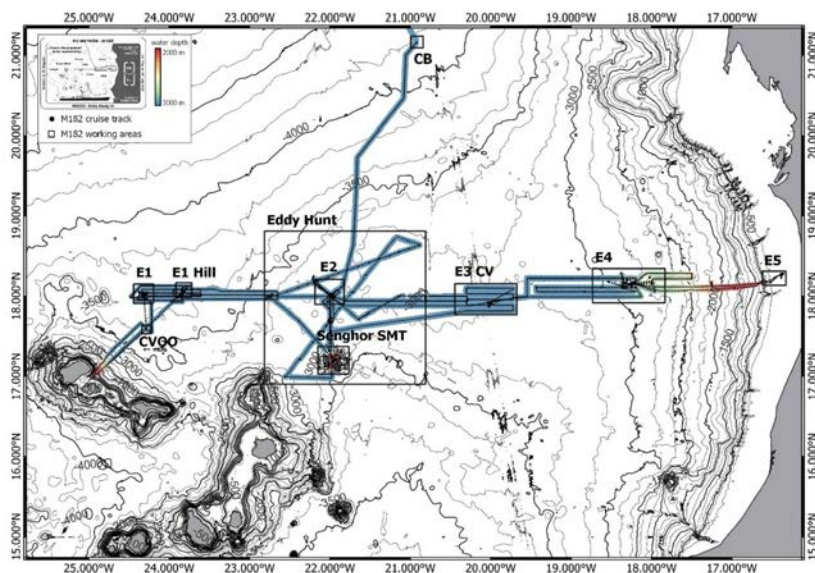


Figure 1: Map with the cruise track, the research areas and bathymetric multibeam data of the cruise M182.

Main outcomes

Initial analyses conducted during M182 provide insights into the physical, biogeochemical, and benthic conditions in the eastern tropical North Atlantic during the study period. A central objective of the cruise was the identification and characterization of a mesoscale eddy west of Mauritania, which was successfully located and sampled through a dense grid of hydrographic, biogeochemical, optical, and biological measurements. However, early observations indicate that the eddy exhibited unusually low biological activity. Water-column fluorescence and chlorophyll-a concentrations throughout the eddy interior were markedly low, with phytoplankton biomass remaining below 0.5 mg m^{-3} in the core and only slightly higher values recorded along the eddy's periphery. These findings suggest that the eddy either existed in a late, weakened stage or did not support substantial primary production during the time of sampling. This contrasts with expectations that mesoscale eddies often enhance local productivity by inducing vertical nutrient fluxes, and it highlights the dynamic variability in the biological response of such features.

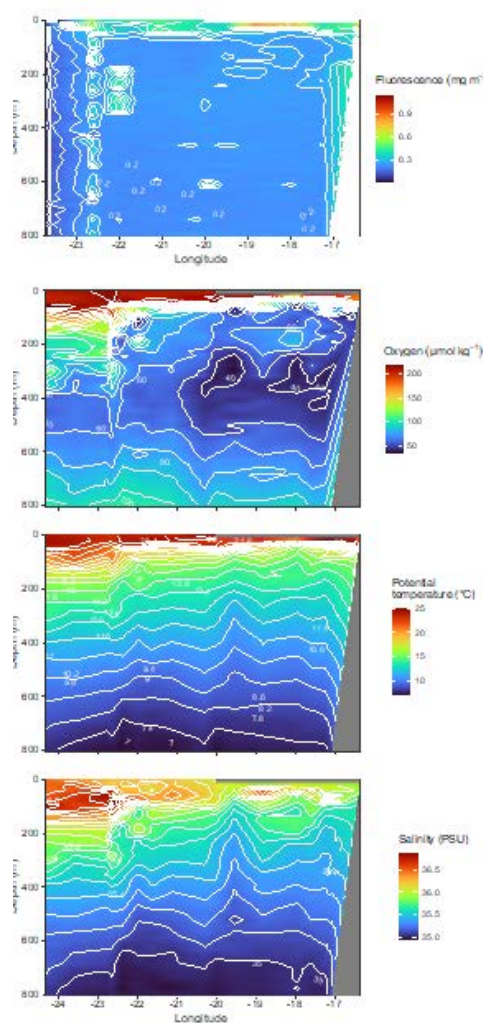


Figure 2: CTD section along the W-S transect including the eddy (center at 17° 32.960' N, 22° 00.017' W). From top to bottom panel: Fluorescence (Chl a) (A), oxygen concentrations (B), potential water temperature (C), and salinity (D). Data is shown for the upper 800 m (but for most CTD casts available to a depth of 20 m above seafloor). Note the x-axis is shifted in panel A because the CTD cast M182_005 was excluded from analysis due to missing sensor data.

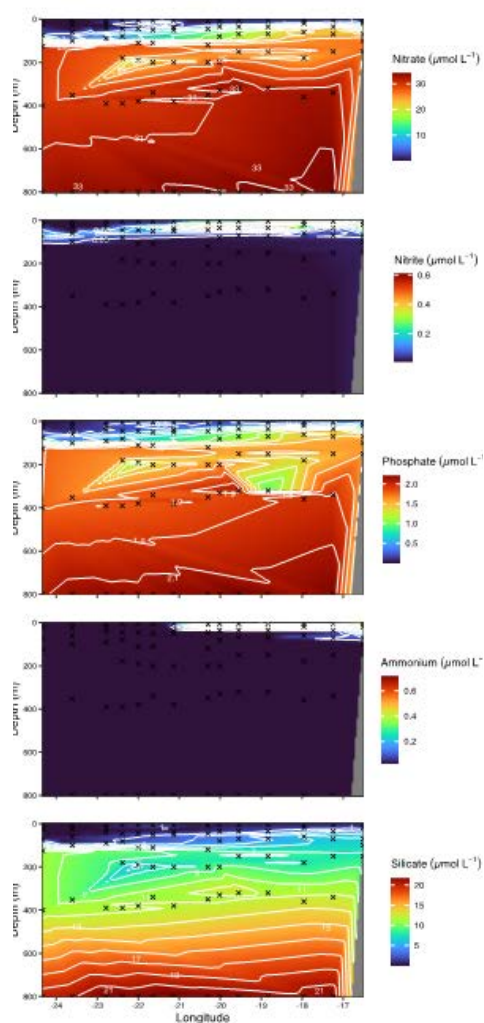


Figure 3: CTD section along the W-S transect including the eddy center (17° 32.960' N, 22° 00.017' W). From top to bottom panel: (A) nitrate (NO_3^-), (B) nitrite (NO_2^-), (C) phosphate (PO_4^{3-}), (D) ammonium (NH_4^+), and (E) dissolved silica (SiO_2). Crosses indicate sampling points. Data is shown for the upper 800 m (but available to depths of ~3000 m).

Despite the low apparent productivity within the eddy, several biogeochemical indicators revealed important spatial patterns. As the ship transited from the eddy region toward the continental margin, concentrations of gel-like colloidal particles – specifically transparent exopolymer particles (TEP) and Coomassie-stainable

particles (CSP) – increased consistently. These particles, which form from phytoplankton exudates and play a significant role in the formation of fast-sinking aggregates, are key agents of carbon export. Their elevated abundance near the coast indicates regionally enhanced particle production or aging of organic matter, potentially linked to different plankton communities or nutrient regimes. These gradients may also reflect the transition from oligotrophic offshore waters to more productive zones influenced by coastal upwelling.

Parallel to water-column observations, extensive seafloor mapping and benthic surveys revealed pronounced spatial heterogeneity in deep-sea habitats across the study region. High-resolution multibeam bathymetry documented complex topographic features, including abyssal hills, seamount structures, and a previously under-characterized submarine canyon with steep walls and variable sediment accumulation.

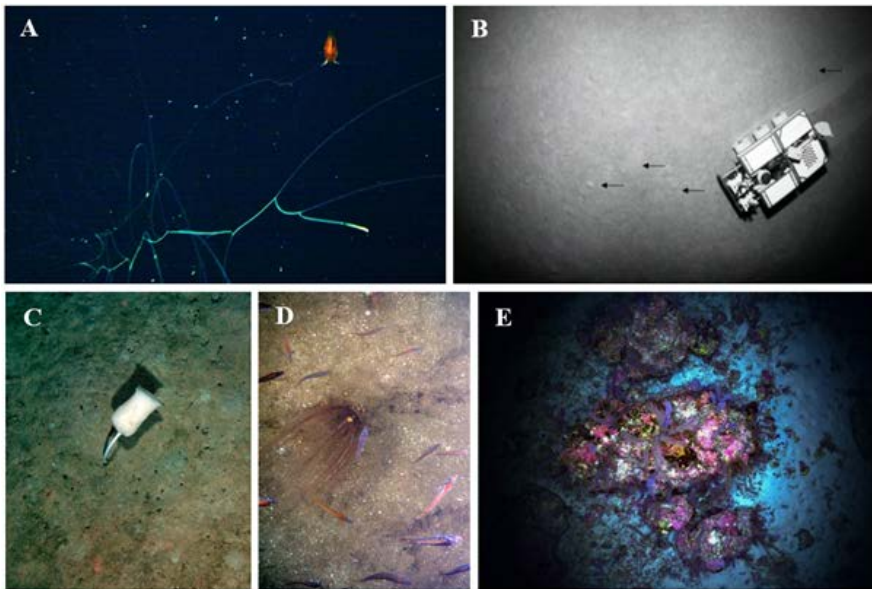


Figure 4: **A:** Observations from horizontal pelagic tows with the stereo camera on the XOFOS frame showing a *Vampyroteuthis* sp. **B:** DSR Panta Rhei as viewed from the AUV ABYSS flying over it in a distance of about 4 m; converted into black & white to enhance contrasts nicely showing details of the seafloor such as cones, irregular or circular arrangements of worm holes (arrows) as well as the tracks of the DSR. **C:** Photo taken with the XOFOS in E4, showing a glass sponge. **D:** Crinoid and small fish in area E5 off the Mauretanian coast. **E:** Photo taken by AUV ANTON from Senghor Seamount.

Such morphological variability is likely to influence local hydrodynamics, sediment deposition, and benthic community structure. Seafloor imagery obtained with the towed camera system showed distinct differences in sediment appearance and composition from west to east. Western areas were dominated by coarse, foraminiferal-rich sediments, while eastern locations exhibited finer, more

terrigenous-rich deposits. These sedimentological contrasts corresponded with clear differences in benthic megafauna density and distribution, with several taxa displaying strong regional preferences. Numerous burrows, tracks, and feeding traces provided evidence of active bioturbation, underscoring the ecological significance of these deep-sea communities (Mbani & Greinert, 2025). The first deployments of benthic landers and the deep-sea rover further demonstrated active carbon cycling at the seafloor. Although full processing of flux and respiration data awaits long-term lander retrieval, preliminary in situ measurements point to measurable oxygen consumption and sedimentary organic matter turnover, even in regions where surface productivity appeared low. This suggests that carbon delivered to the seabed – whether from eddy-driven processes, lateral transport, or episodic events – continues to support benthic metabolic activity.

Collectively, these preliminary findings highlight a system characterized by strong spatial variability and unexpected biological signals. The low productivity inside the sampled eddy, coupled with enhanced particle concentrations and sediment complexity near the continental margin, illustrates the intricate interplay between physical structures, biogeochemical processes, and benthic ecosystems. Further post-cruise analyses of water-column chemistry, particle composition, sediment cores, and benthic flux measurements will be essential to disentangle the drivers of these patterns and to assess the role of mesoscale eddies in regional carbon cycling.

Suitability of RV METEOR

RV METEOR with its size and technical capabilities and equipment is very well suited for the needed tasks at sea. Decks crew, bridge officers and scientific crew form a very well operating unit that know each other's competences, know the gear that is used and how it is deployed. After correcting the position offsets, the ship's multibeam systems work very well and provided good data. Since METEOR is not equipped with a fibre optic cable, the GEOMAR winch had to be brought on board, which reduced the available deck-space. There were problems with the ship's Posidonia navigation system, which could be solved by changing offsets. Even though, METEOR has no DP steering, it could maneuver precisely, which was important for the deployment and retrieval of the AUVs and landers.

Scientific Output

List of Publications

Mbani B & Greinert J, Automated underwater image analysis reveals sediment patterns and megafauna distribution in the tropical Atlantic. Scientific Reports 2025, 15. <https://doi.org/10.1038/s41598-025-12723-y>

Cruise Report

M182: https://doi.org/10.48433/cr_m182

M183

Site Survey for Ridge Flank Observatory Science on the Southern Reykjanes Ridge

Authors

MARUM – Center for Marine and Environmental Sciences | Bremen, Germany
W. Bach, C. Nadolsky, R. Bernhard, A. Kopf, S. Kasten and M183 Scientific Party

Summary

Cruise M183 took place to collect site survey data of the eastern flank of the southernmost Reykjanes Ridge to identify potential targets for MeBo-drilling and ridge flank observatory installation. Survey data to be collected included multibeam echosounding and subbottom profiling, porewater analyses of cored sediment, and temperature measurements in the shallow subseafloor. The survey work began in the area between 58°00'N, 32°W and 58°10'N, 31°W (Figure 1), but suitable sediment ponds were not found in that section of the ridge flank. We were successful in identifying the third pond we visited as promising target for MeBo drilling and ridge flank observatory installation. In this sediment pond (named Squid Pond by us) violine-bow heat flow probe deployments yielded a tight data grid that clearly suggests significantly higher heat flow on the northwestern side of the pond and the adjacent ridge than in the respective counterparts on the southeastern side of the sediment pond. After two subbottom profiling dives with ROV MARUM SQUID, the robot was used in and around Squid Pond to collect rocks and push-core sediments. Twelve gravity cores were taken; the most common type of sediment is sandy to clayey ooze with variable color (dominantly grayish brown to bluish gree) and fluctuating fractions of foraminiferal sand, spiculite, and dropstones. Sediment pore water samples were retrieved and analyzed for oxygen and iron concentrations as well as total alkalinity. We find persistent low oxygen concentrations in multiple sediment layers that alternate with zones of elevated iron concentrations, where as dissolved Mn is high in concentration throughout the cored sediment. Also, O₂ concentrations increase towards the sediment-basement interface. The combined heat flow and geochemical data suggest an upward-directed flow of basement fluids in the ridge bounding Squid Pond to the northwest.

Heat Flow Constraints on Subseafloor Seawater Circulation

In-situ temperature gradients, thermal conductivity data, and bottom water temperature profiles were used to study variations in heat flow within and around Squid Pond, a sediment pond on the eastern flank of the Reykjanes Ridge overlying basement 3–3.5 million years of age (Figure 1).

Heat flow in general is lower than predicted by conductive lithospheric cooling for 3 Ma slow spread crust (around 250 mW/m^2). However, heat flow is very unevenly distributed (Figure 2) with values ranging from as low as $< 20 \text{ mW/m}^2$ to much higher values (up to 560 mW/m^2).

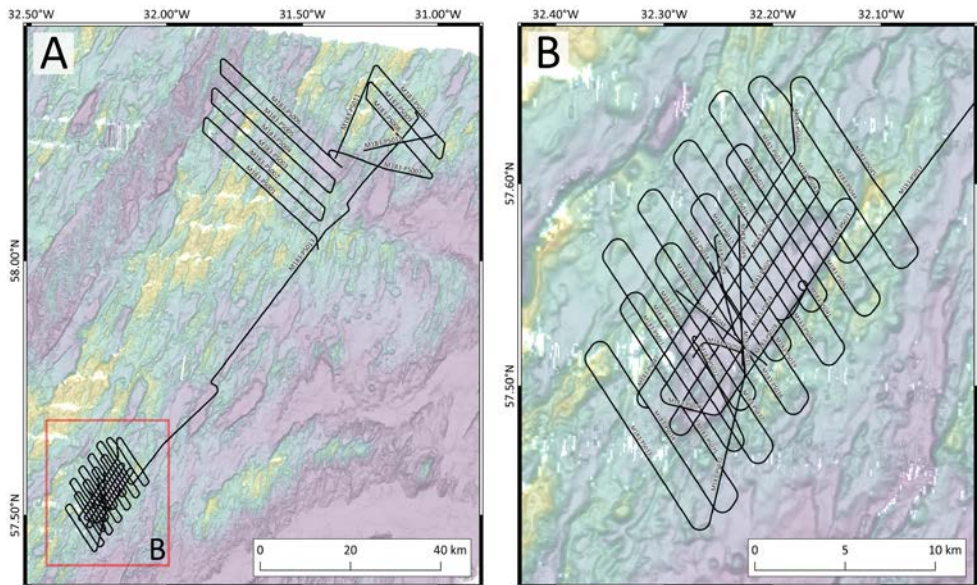


Figure 1: (a) Survey track lines in the M183 work area on the eastern flank of the southern Reykjanes Ridge (b) close-up of the Squid Pond area.

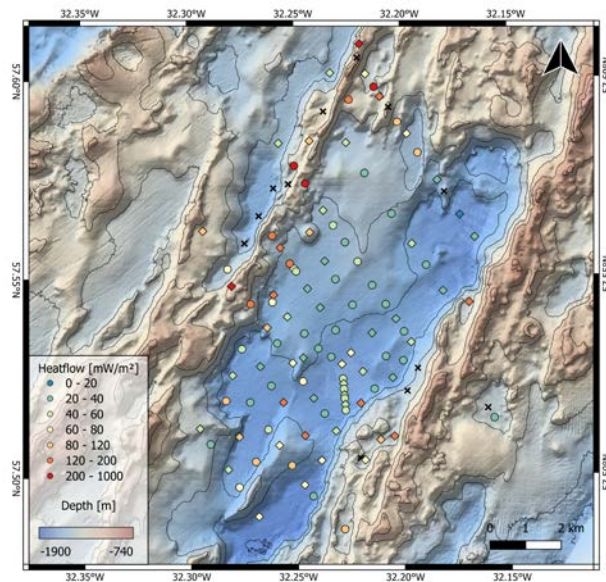


Figure 2: Bathymetric map of Squid Pond with results of heat flow measurements. Note the large range of heat flow values, which are particularly low in the southeastern part of the sediment pond and high on the ridge bounding the pond in the northwest. "x" denotes failed attempts.

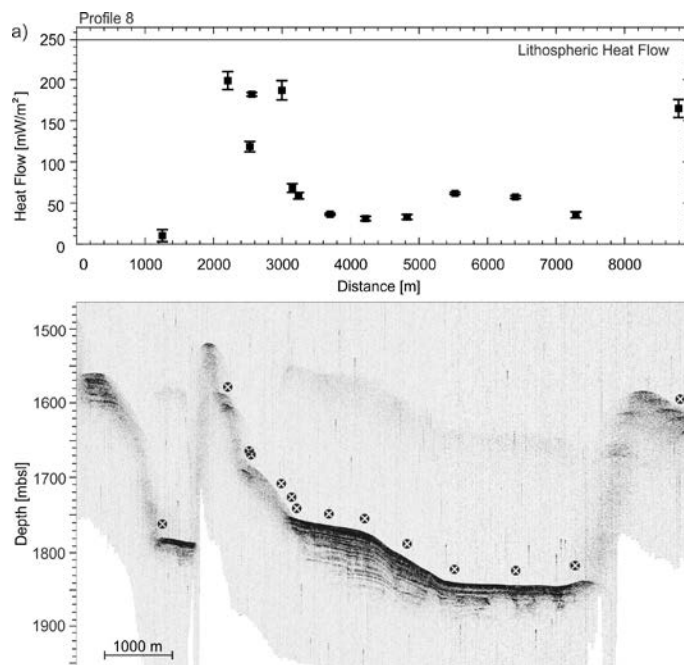


Figure 3: Representative SE-NW section through Squid Pond, showing sub-bottom profiler (PARASOUND) data and sites of data collection (lower panel) and the distribution of heat flow density values (upper panel).

Numerical modeling (COMSOL Multiphysics) was used to test whether conductive heat transport alone could account for the observed heat flow on the eastern ridge flank, factoring in topography, sediment thickness, and seafloor temperatures. The results clearly indicate that the heat flow distribution cannot be explained without NW-directed seawater flow underneath the sediment cover. This supports the idea that warm fluids diffuse upward through basement outcrops on the northwestern margin of Squid Pond. However, discrepancies between the conductive model and field observations indicate that additional mechanisms – such as hydrothermal circulation between outcrops – also play a role in redistributing heat in the region.

Upward Oxygen Diffusion and a Novel Geochemical Zonation

It has been known for some time that oxygen supplied by circulating basement fluids supplies oxygen to microbial communities inhabiting deepsea sediments (e. g., Orcutt et al. 2011). Our results of the ex-situ oxygen concentration in the retrieved sediments revealed distinct differences between sediments located in depressions with high sediment thicknesses (e. g., inside Squid Pond) and sediments from the ridges covered only by a thin sediment layer. At the ridge site, ex-situ oxygen data reveal upward diffusion of oxygen from hydrothermal fluids into the overlying sediment. This is evident by a C-shaped oxygen profile (Figure 4).

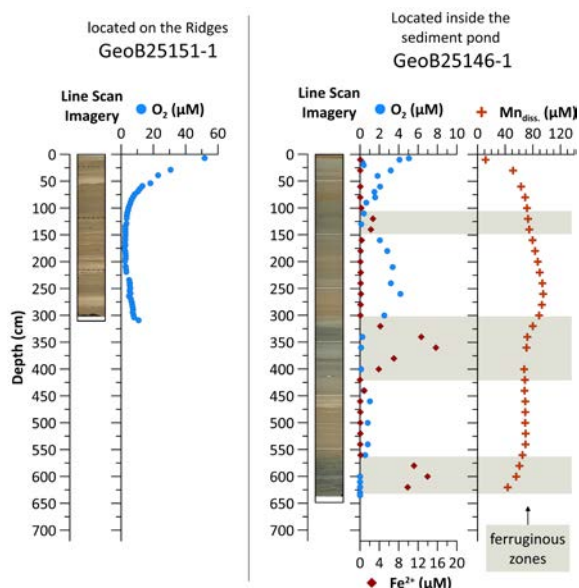


Figure 4: Pore-water geochemistry data of two cores from M183. Left: Ex-situ oxygen concentration profile alongside the line scan image of GeoB25151-1 from the eastern Ridge of Squid Pond. Right: Ex-situ oxygen concentration, Fe²⁺, and dissolved Mn concentration alongside the line scan image of GeoB25146-1 located inside Squid Pond (modified after Nadolsky et al., in prep.).

In contrast, the sediments from inside Squid Pond reveal distinct geochemical zones: intervals with significant oxygen concentrations (up to 6 μM) but no detectable dissolved iron alternate with sediments that are oxygen-free but have up to 16 μM dissolved Fe^{2+} in the pore water. This intercalation of oxic and ferruginous layers is expressed in changes between brownish (O_2) to bluish-grey (Fe) colors of the sediment cores. This variability in the contents of dissolved O_2 and Fe is contrasted by uniformly high concentrations of Mn^{2+} throughout the entire core section, which spans a sedimentation period of up to 200 kyr (Nadolsky et al., in prep.). The pore water profiles of Squid Pond hence deviate noticeably from the classical redox cascade model of Froelich et al. (1979), which predicts complete oxygen consumption in near-seafloor sediments before Fe- and Mn-reduction dominate.

Based on comprehensive pore water and solid-phase geochemical, sedimentologic, and stratigraphic analyses, we investigated the environmental conditions and geochemical processes responsible for this novel redox zonation (Nadolsky et al., in prep.). The ferruginous layers coincide with high rates of sedimentation and organic carbon accumulation. However, even within the same depositional region, localized sediment accumulation dominates over broader climatic signals and leads to distinct redox zonation.

The preservation of alternating geochemical zones is remarkable given that diffusive processes should homogenize pore-water chemistry over such extended timescales (>200 kyr). Nadolsky et al. (in prep.) attribute this preservation to a combination of diffusion-limiting sediment heterogeneity, including zoophycos burrows and sponge spicules that create geochemical microenvironments.

Their results reveal that oxic conditions extend far beyond the typical near-seafloor or hydrothermally driven near-basement zone, but reappear at considerable sediment depths. These findings have broader implications for understanding organic carbon preservation in widespread ridge flank sediments and demonstrate how localized sediment accumulation dominates sedimentary and diagenetic processes in this setting.

References

Froelich P, Klinkhammer GP, Bender ML, Luedtke NA, Heath GR, Cullen D, et al., Early oxidation of organic matter in pelagic sediments of the eastern equatorial Atlantic: suboxic diagenesis, *Geochimica et Cosmochimica Acta* 1979, 43(7), doi: 10.1016/0016-7037(79)90095-4.

Nadolsky C, Bach W, Bethke D, von Dobeneck T, Frederichs T, Geibert W, Kopf A, Miramontes E, Raddatz J, Schmidt C, Siegburg M, Volz J & Kasten S, Alternation of oxic and ferruginous intervals in pond sediments of Reykjanes Ridge, North Atlantic, in prep.

Scientific Output

List of Publications

Nadolsky C, Bach W, Bethke D, von Dobeneck T, Frederichs T, Geibert W, Kopf A, Miramontes E, Raddatz J, Schmidt C, Siegburg M, Volz J & Kasten S, Alternation of oxic and ferruginous intervals in pond sediments of Reykjanes Ridge, North Atlantic, in prep.

Bernhard R, Heat Flow Pattern at the Reykjanes Ridge: Hydrothermal Circulation beneath a Sedimentary Basin and Along the Eastern Ridge Flank. M.Sc. Thesis, University of Bremen.

List of conference presentations

2025 | **Alternation of oxic and ferruginous intervals in pond sediments of Reykjanes Ridge**, North Atlantic Ocean Goldschmidt Conference, Prague, Czech Republic.

Data

Ship track:
<https://doi.pangaea.de/10.1594/PANGAEA.954531>

Bathymetry:
<https://doi.pangaea.de/10.1594/PANGAEA.965760>

Heat flow:
<https://doi.pangaea.de/10.1594/PANGAEA.963329>

Physical oceanography (CTD):
<https://doi.pangaea.de/10.1594/PANGAEA.964069>

Hydrochemistry:

<https://doi.pangaea.de/10.1594/PANGAEA.964078>

Thermosalinograph:

<https://doi.pangaea.de/10.1594/PANGAEA.962910>

Cruise Report

M183: https://doi.org/10.48433/cr_m183

M184

Process understanding and long-term variability in the Labrador Sea

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

J. Karstensen, A. F. Dilmahamod

Overview

The scientific program of the RV METEOR M184 expedition was dedicated to studies on high latitude water mass transformation, hydrographic & currents variability, and submesoscale dynamics that is associated with oceanic frontal regions in the Labrador Sea and the Irminger Basin. Measurements of the vertical structure of temperature, salinity, density, oxygen, nutrients, optical properties and the flow were performed at selected stations making use of a CTD instrument and a rosette sampler. Close to the surface, continuous recordings using the ships thermosalinograph (temperature, salinity), meteorological sensors, bathymetry, and Acoustic Doppler Current Profiler (ADCP) for ocean current observations have been carried out. For submesoscale resolving frontal surveys, we deployed two autonomous underwater electric gliders and 38 surface drifter. Moreover, profiling CTDs (Moving Vessel profiler and underway CTDs) were operated from the moving ship (Figure 1). In total, nine deep sea moorings have been re-deployed. The expedition was a contribution to international programs (OSNAP) and projects (EuroSea, GROOM II).

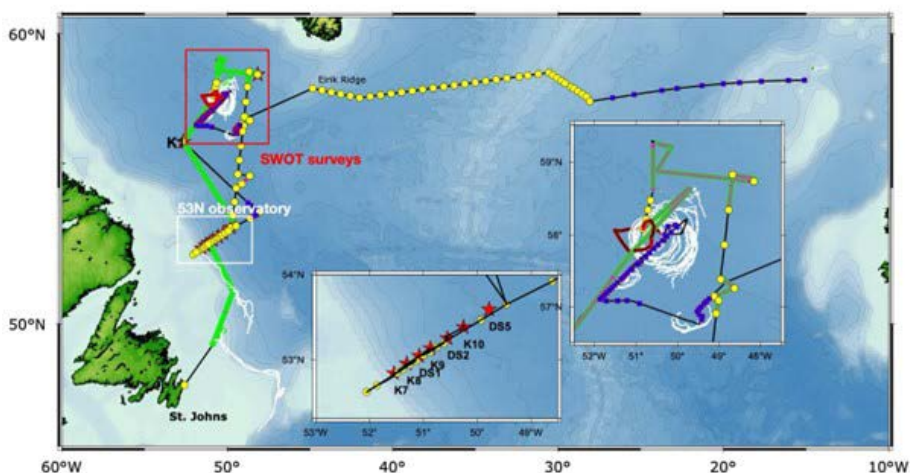


Figure 1: Chart of R/V METEOR M184 cruise with underway data acquisition tracks (ADCP, TSG; bathymetry; meteorology; all along the black line) and sampling stations (mooring, red stars; CTD+, yellow dots; uCTD, blue dots, MVP green squares). Tracks (only during the cruise) of surface drifters we deployed (white lines). Inset maps: 53°N observatory (lower middle); mesoscale eddy survey (right).

Longterm moorings & amoc

One major objective of the cruise was the re-deployment of long-term moorings. Our operations focussed on three regions: the 53°N observatory at the exit of the Labrador Sea (Zantopp et al. 2017), the K1 mooring in the central Labrador Sea deep convection area, and three moorings of western Greenland. While the 53°N observatory and K1 both have been established in 1997 and operated since (with various degrees of completeness), the US (WHOI) array started in 2014 with the set-up of the international Overturning in the Subpolar North Atlantic (OSNAP) program (Lozier et al. 2019). Given the cyclonic circulation within the Labrador Sea a boundary current (BC) array as the 53°N observatory can provide the current and hydrography and eventually tracer (e. g. oxygen) variability in the BC. Such observations helped to develop a rather comprehensive understanding of dynamical processes in the BC and also provide ground truth data for assessment of simulations. Making use of the M184 in combination with earlier data and linked to satellite sea surface height observations, one recent focus was to analyse if the width of the BC from satellite data reveals systematic changes in the interior structure of the boundary current. This was analysed using ship sections over the BC as well as mooring data (Figure 2).

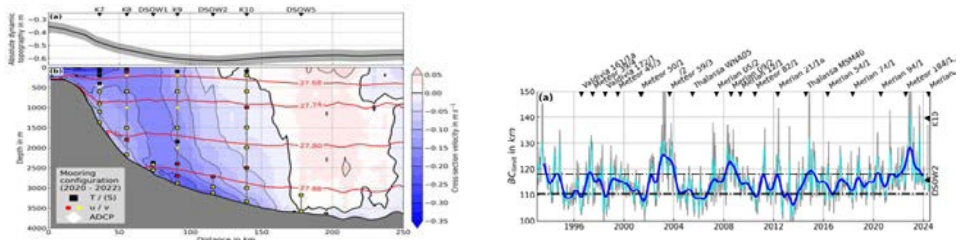


Figure 2: (left) Mean velocity section from 20 realizations across the 53°N observatory aligned with the local topography considering data. The mooring configuration from 2020 to 2022 is indicated; blue (red) colours indicate flow out of (into) the Labrador Sea. (right) Temporal evolution of the separation between flow into and out of the Labrador Sea as derived from satellite observations of the dynamic topography from 1993 to 2024. The timing of research expeditions is indicated by the triangles (with respective cruise names) and the position of two moorings in the array (DSOW2 at 120 km and K10 at 140 km) is labelled on the left. Blue line is the 13-month low pass filter time series (black line). (pers. comm. Jörg Fröhle).

From the boundary current width analysis (Fröhle et al. in prep) it is found that during phases of a narrower (wider) surface current, the DWBC flow structure is more baroclinic (barotropic), accompanied by a weakening (strengthening) of the deep core. The dominant mode of variability of the width of the surface current is at interannual time scales (Figure 2 right) and correlated with the subpolar gyre strength and size. Also, correlations with the strength of the wind stress curl over the subpolar North Atlantic is found. Another mechanism is through wind stress curl-induced sea surface height anomalies east or south of Greenland, which are advected by the mean currents into the Labrador Sea and to the 53°N observatory.

Since 2014 the 53°N observatory and two/three short moorings off the west coast of Greenland are contributions to the international observing array that measure the overturning strength across nominal 60°N, known as OSNAP (Lozier et al. 2019). This array is augmenting the overturning observations across the RAPID array at normal 26°N that is operated since 2004. The 2 years of moored instruments data that has been recovered during M184 provides a significant contribution to constraining the western Subpolar North Atlantic aka Labrador Sea overturning transport (volume, heat, freshwater) (Figure 3). In the most recent publication of the full array and covering eight years of data, from 2014 to 2022 (Figure 3), that enabled Fu et al. (in press) estimate that a single boundary current captures ~30% of subpolar MOC interannual variability.

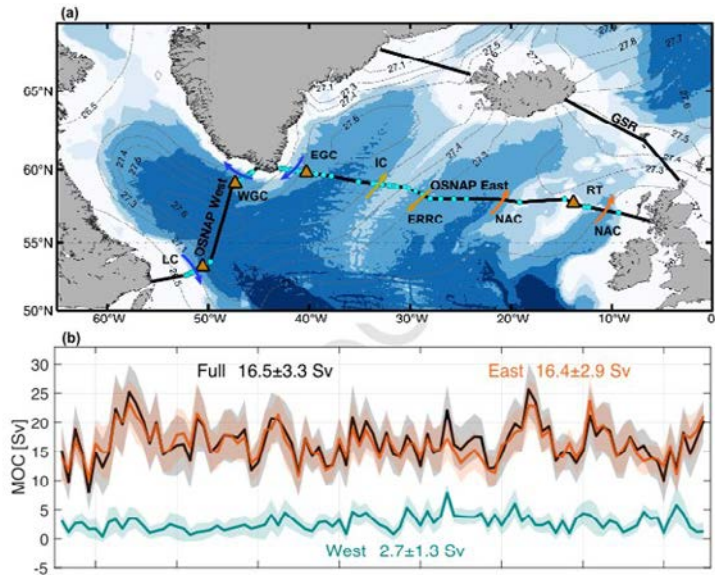


Figure 3: (upper) configuration of the OSNAP array (west and east) and the Greenland-Scotland-Ridge (GSR) section (thick black lines). OSNAP mooring positions are marked by cyan dots. Orange triangles mark the offshore extent of boundary current regions: Rockall Trough, East Greenland Current (EGC), West Greenland Current (WGC) and Labrador Current (LC). Arrows illustrate horizontal currents: North Atlantic Current (NAC), East Reykjanes Ridge Current (ERRC), Irminger Current (IC). (lower) Monthly overturning circulation time series across the full OSNAP array (black), OSNAP East (orange), and OSNAP West (cyan) from Fu et al. (2025). Shading indicates monthly uncertainty estimated from a Monte Carlo analysis (Lozier et al. 2019).

(Sub)mesoscale surveys

During the M184 expedition, in August-September 2022, an extensive submesoscale-resolving multiplatform experiment was conducted across an Irminger Ring in the Labrador Sea (Figure 4). Guided by real-time access to now and forecast products the approximate locations of mesoscale structures were determined. One candidate Irminger Ring was identified and a ship survey started that allowed approximating the eddy center by fitting an idealized eddy using the vessel mounted ADCP data (Bendinger et al. 2025). The survey was refined by deploying two underwater electric gliders equipped with nitrate, microstructure shear, chlorophyll fluorescence, oxygen, and turbidity sensors. The gliders operated in concert with a variety of ship operated instruments including underway-CTD's, a moving vessel profiler, Thermosalinograph, ADCPs and a X-band radar system on RV METEOR. Observations were acquired both, along the peripheries and within the core of the eddy, and offered insight into submesoscale dynamics of the ring. Making use of nearly concurrent turbulence and nutrients observations, we estimated the vertical flux pattern across the eddy's frontal and interior regions. From the recorded and expected glider vehicle motion a vertical

water velocity could be inferred and compared with the nutrient flux pattern. The stability of the ring was tracked with surface drifters, for weeks after the ship and glider survey ended.

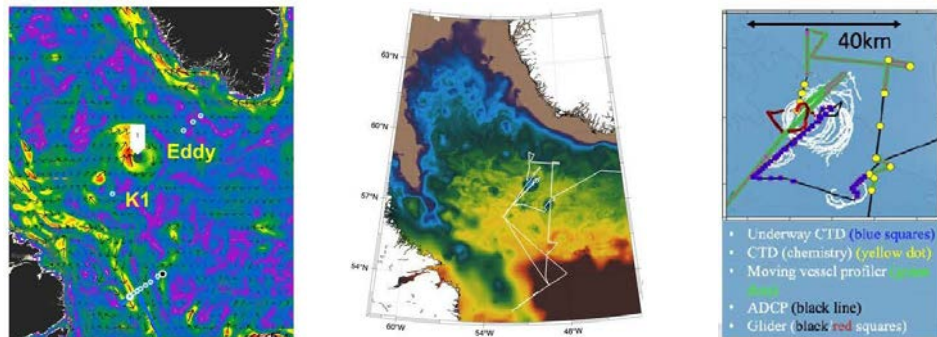


Figure 4: (left) Web-browser map of nowcast surface speed during M184 accessed on the ship. The candidate Irminger Ring is indicated by the label Eddy. (middle) Satellite based GHRSSST sea surface temperature map of the 29 Aug 2022 with M184 ship tracks overlaid. The candidate Eddy from left is seen as a cold temperature signature crossed by many ship tracks (white lines). (right) Detailed map of the candidate Eddy (Irminger Ring) surveys during M184 – devices deployed are recoverable from the legend.

Cruise limitations

The cruise was originally proposed for RV MARIA S MERIAN because we needed to enter regions that IMO declared as “Polar Waters” and where RV METEOR is not allowed to enter. Therefore we could not re-deployed two mooring offshore western Greenland that fortunately were re-deployed by US colleagues from WHOI, USA. Likewise, no data (particularly CTD/IADCP, underway data) could be sampled closer to western and eastern Greenland and therefore we were unable to record a synoptic picture of the Deep Western Boundary Current.

References

- Bendinger A, Dilmahamod AF, Albert A, Le Sommer J & Karstensen J, Characteristics of Mesoscale to Submesoscale Eddies in the Labrador Sea: Insights from Ship Observations, *J. Phys. Oceanogr.* 2025, <https://doi.org/10.1175/JPO-D-24-0216.1>, in press.
- Fu Y, et al., Characterizing the interannual variability of North Atlantic subpolar overturning, *Geophysical Research Letters* 2025, 52, e2025GL114672. <https://doi.org/10.1029/2025GL114672>.

Lozier MS, et al., A Sea Change in Our View of Overturning – First Results from the Overturning in the Subpolar North Atlantic Program, *Science* 2019, 363, 516–521, doi: 10.1126/science.aau6592.

Zantopp R, Fischer J, Visbeck M & Karstensen J, From interannual to decadal: 17 years of boundary current transports at the exit of the Labrador Sea, *J. Geophys. Res. Oceans* 2017, 122, doi:10.1002/2016JC012271.

Scientific Output

List of Publications

Fu Y, et al., Characterizing the interannual variability of North Atlantic subpolar overturning, *Geophysical Research Letters* 2025, 52, e2025GL114672.
<https://doi.org/10.1029/2025GL114672>.

Horstmann J, et al., Surface Drifter Data of the Labrador Sea: Positions of Lagrangian Hereon Drifters Deployed in the Labrador Sea during Meteor Cruise M184 [dataset publication series], PANGAEA 2024,
<https://doi.org/10.1594/PANGAEA.967715>.

Karstensen J, Wöfl A-C, Multibeam bathymetry raw data (Kongsberg EM 122 entire dataset) of RV METEOR during cruise M184 [dataset], PANGAEA 2023,
<https://doi.org/10.1594/PANGAEA.953612>.

Karstensen J, Schlundt M & Krahmann G, Continuous thermosalinograph oceanography along RV METEOR cruise track M184 [dataset], PANGAEA 2023,
<https://doi.org/10.1594/PANGAEA.958396>.

Karstensen J, Krahmann G, Dilmahamod AF, (submitted) Physical oceanography (CTD) during METEOR cruise M184 [dataset]. PANGAEA,
<https://doi.pangaea.de/10.1594/PANGAEA.986330>.

Glösen L, (2022) Observed relative dispersion in Labrador Sea Eddies in Summer 2022, BSc thesis, CAU University, Kiel, Germany.

Kunst T, Characterizing mesoscale eddies in the Labrador Sea based on data from moored observations 2023, MSc thesis, CAU University, Kiel, Germany.

Ripke K, Long Term hydrographic variability from ship and moored observations in the Labrador Sea, 2024, BSc thesis, CAU University, Kiel, Germany.

List of conference presentations

2022 | 25 years of Eulerian time series observations at the exit of the Labrador Sea – the 53°N array, AGU Fall meeting, Chicago/USA (virtual attendance)

2023 | The 53°N observatory: 25 years time series data from the exit of the Labrador Sea, 6th Xiamen Symposium on Marine Environmental Sciences, Xiamen, China(virtual attendance)

2024 | Subpolar eddies from a high-resolution, multiplatform experiment in the Labrador Sea, EGU 2024, Vienna/Austria

2024 | Subpolar eddies from a high-resolution, multiplatform experiment in the Labrador Sea, Ocean Sciences Meeting, New Orleans/USA

2024 | Transport and Modification of Overflow Waters in the Subpolar North Atlantic, Ocean Sciences Meeting, New Orleans/USA

2024 | The meridional overturning circulation in the North Atlantic: insights from OSNAP, Ocean Sciences Meeting, New Orleans/USA

Data

Surface Drifter Data (Positions):
<https://doi.org/10.1594/PANGAEA.967715>

Multibeam bathymetry raw data:
<https://doi.org/10.1594/PANGAEA.953612>

Continuous thermosalinograph:
<https://doi.org/10.1594/PANGAEA.958396>

Physical oceanography (CTD):
<https://doi.pangaea.de/10.1594/PANGAEA.986330>

Physical oceanography (IADCP):
in submission

Physical oceanography (vmADCP):
in submission

Cruise Report

M184: https://doi.org/10.48433/cr_m184

M185

Assessing Oceanic Impacts on Arrival and Transport of European eel larvae

Authors

Thünen Institute of Fisheries Ecology | Bremerhaven, Germany

R. Hanel, L. Marohn, M. Freese, K. Wysujack, J.-D. Pohlmann

Bremen University, BreMarE | Bremen, Germany

H. Auel, G. Voss, K. Kremer

AZTI | Sukarrieta, Spain

L. Ferrer, C. Claver

Universidad de Las Palmas de Gran Canaria | Las Palmas, Spain

M. Couret, J. Díaz-Pérez

Charles University | Prague, Czech Republic

Z. Musilová, Z. Konvičková

National Oceanography Centre | Southampton, UK

J. Williams, W. Major

and the M185 scientific party

Introduction

Understanding biological processes and transport mechanisms at the ocean–continent boundary is key to unraveling how biodiversity patterns, trophic interactions and carbon fluxes are shaped in the North Atlantic. While the European continental slope and the Strait of Gibraltar are recognized as major gateways for water mass exchange and organismal transport, their ecological role has been insufficiently studied. In this context, RV METEOR cruise M185 (29 October – 26 November 2022, Hamburg–Lisbon) brought together an interdisciplinary team to investigate larval fish distributions, zooplankton-mediated carbon flux, environmental DNA signatures, and adaptive traits of mesopelagic organisms.

A particular focus was placed on the oceanic influences on the abundance, distribution and recruitment mechanisms of the European eel (*Anguilla anguilla*), whose declining recruitment is of major management concern.

Eel larvae and recruitment processes

During cruise M185, a total of 31 *A. anguilla* larvae were caught between the Iberian Peninsula and the Alboran Sea. In contrast, no eel larvae were collected in the Bay of Biscay. As documented in the cruise report and the associated publication by Marohn et al. (2025), sampling effort in this region had to be reduced substantially due to adverse weather conditions, so the absence of catches cannot alone be interpreted as evidence of low abundance. Nevertheless, the reanalysis of historical ichthyoplankton survey demonstrates that larval densities in the Bay of Biscay were already markedly lower than along the Iberian slope during the 1970s and 1980s, and that catches declined further after the onset of the recruitment collapse in the early 1980s. While some surveys in the 1970s yielded high larval catches, abundances dropped by an order of magnitude in the following decade. The present results thus fit into a long-term pattern, with late-stage larval abundance decreasing in parallel with glass eel recruitment. This correspondence suggests that no disproportionately increased mortalities occur during the final larval drift across the continental slope.

In addition, the case study in the Strait of Gibraltar carried out during M185 provided new insights into the recruitment mechanisms that control the transport of eel larvae into the Mediterranean Sea and adjacent areas (Freese et al., 2025). A 24-hour station with repeated IKMT hauls combined with CTD and ADCP data showed that leptocephali of *A. anguilla* are most likely transported into the Mediterranean under conditions where nocturnal vertical migration coincides with strong eastward surface currents. These findings highlight the importance of small-scale hydrographic processes and selective tidal transport as drivers of basin-scale recruitment dynamics.

Oceanographic measurements (ADCP)

Ocean current velocities from ~37 m to 1600 m depth were continuously collected with a vessel-mounted 38 kHz Ocean Surveyor ADCP. The system provided high-resolution vertical profiles of horizontal velocity with 16 m bins, averaged over 2 minutes (Hanel et al., 2023). The most striking patterns were recorded during the 24-hour station in the Strait of Gibraltar, where maximum depths of ~626 m were reached. The data highlight the strong and highly variable currents in this bottleneck region, which directly shape larval drift and recruitment into the Mediterranean. These measurements, together with historical datasets, provide a

physical basis for interpreting larval transport patterns of European eel (Freese et al., 2025).

Zooplankton food web and carbon fluxes

Mesozooplankton communities were studied with 28 MultiNet hauls. Biomass was generally low in late autumn, with cyclopoid and small calanoid copepods dominating surface layers, while larger copepods were rare. Regional differences included salp blooms off northern Spain and krill dominance (*Meganyctiphanes norvegica*) along the Portuguese continental rise. Stable isotope analyses revealed a complex trophic web with only a few strictly herbivorous species and many omnivores and carnivores.

Carbon flux processes were examined at two 24-hour flux stations. Combining zooplankton respiration, Electron Transfer System (ETS) activity, Marine Snow Catcher deployments and in situ camera observations, the relative contributions of gravitational flux and active flux by migrant zooplankton, euphausiids, decapods, and mesopelagic fishes were quantified. Results confirmed strong diel differences, with higher migrant biomass and diversity at night. These processes illustrate the biological carbon pump and its variability in the Iberian region, providing essential input for global carbon cycle models.

Environmental DNA analyses

Seawater samples were collected at 17 vertical profiles across the study area, resulting in 102 samples at depths from 10 to 1000 m. DNA extracted from Sterivex filters was amplified with a fish-specific marker (Teleo) and sequenced. In total, 29 orders, 49 families, 75 genera, and 77 species were identified, including 70 Actinopterygii and 7 Elasmobranchii.

Small pelagic species such as sardine (*Sardina pilchardus*) dominated in the Bay of Biscay and off Galicia (~30% of reads). Mesopelagic lanternfishes (*Myctophum punctatum*, 15%; *Benthosema glaciale*, 9%) were abundant throughout the cruise area, while *Anguilla anguilla* was detected in very low abundance (<1.2%) at two stations (off Portugal and in the Mediterranean). Diel vertical migration signals were reflected in eDNA profiles, with *M. punctatum* more abundant near the surface at night. Deep-sea sharks such as *Hexanchus griseus* were also detected below 700 m, highlighting the potential of eDNA for assessing mesopelagic biodiversity.

Visual adaptations of mesopelagic fishes

Over 100 mesopelagic fishes from six orders were sampled for retinal transcriptomics and morphological studies. Preliminary analyses show that most species rely predominantly on rod opsins (implicating the rod-only retinas), with many exhibiting blue-shifted rhodopsin variants. We found that the most common visual system is based only on one rod opsin gene (RH1) as found in dragon fishes (Stomiiformes), some lanternfishes (Myctophiformes), or in slickheads (Alepocephaliformes). An enhanced visual system makes use of either multiple rhodopsins, such as in some lanternfishes (*Myctophum* sp.), spinyfins (Diretmidae, Trachichthyiformes) and deep-sea eels (*Serrivomer* sp.; Anguilliformes), or it can rely on both rod and cone photoreceptors, as seen in hatchetfishes (*Argyroteleus*; Stomiiformes), frost fishes (*Benthodesmus*; Scombriformes) and pearleyes (*Benthalbella*; Aulopiformes). Comparative datasets generated during the cruise will contribute to broader investigations into the molecular evolution of vision in the deep sea, including multiple rod opsin systems and bioluminescent signalling in stomiiform fishes.

Synthesis and conclusions

Cruise M185 applied an interdisciplinary approach that combined fish biology, zooplankton ecology, environmental genetics, physical oceanography and molecular methods. This integrative framework provided new data on larval transport, trophic interactions and biodiversity patterns in the study region, and forms a basis for future assessments of recruitment dynamics and carbon fluxes. Results of the investigations confirm a persistent decline of late-stage European eel larvae at the continental slope, provide mechanistic evidence of tidal-driven recruitment into the Mediterranean, and advance the understanding of trophic interactions, biodiversity and carbon fluxes in a climatically sensitive region. The datasets generated form a valuable baseline for future monitoring of eel recruitment but also for zooplankton-mediated carbon transport, and allowed further insight into evolutionary adaptations in mesopelagic organisms.

Scientific Output

List of Publications

Freese M, Marohn L, Ferrer L, Pohlmann J-D, Wysujack K, Blancke T & Hanel R
Details on the transport of European eel larvae through the Strait of Gibraltar into the Mediterranean Sea, Scientific Reports 2025, 15, 1006,
<https://doi.org/10.1038/s41598-024-82929-z>.

Marohn L, Wysujack K, Freese M, Pohlmann J-D, Blancke T & Hanel R, Long-term reduction of late-stage European eel larval abundance at the continental slope reflects glass eel recruitment decline, ICES Journal of Marine Science 2025, 82(3), fsaf020,
<https://doi.org/10.1093/icesjms/fsaf020>.

List of theses

Voss G, Trophische Interaktionen des Zooplanktons vor der iberischen Halbinsel, 2023, BSc Thesis, Uni Bremen.

Müller P, Distribution and composition of mesopelagic fish species around the Iberian Peninsula and in the Alboran Sea, 2023, BSc Thesis, Uni Bremen.

Santosh SL, New insights into the feeding ecology of eel larvae in the Sargasso Sea through body composition analyses and molecular imaging, 2023, MSc Thesis, Uni Bremen.

List of conference presentations

2024 | **The late larval stage of the European eel – another blind spot in the life cycle and its potential for stock management.** World Fisheries Congress, Seattle, USA.

2025 | **Leptocephaluslarven des Europäischen Aals (*Anguilla anguilla*) am Kontinentalrand Europas– Ergebnisse der METEOR-Expedition M185.** Annual Conference of the Gesellschaft für Ichthyologie (GfI), Landau, Germany.

2025 | **Expansion of rhodopsin repertoire as a unique visual adaptation in the silver spinyfin (*Diretmus argenteus*).** FASEB Conference – Biology and Chemistry of Vision. Southbridge, Massachusetts

Data

Mastertrack:

<https://doi.pangaea.de/10.1594/PANGAEA.957630>

CTD:

Hanel, Reinhold; Schlundt, Michael; Freese, Marko; Marohn, Lasse; Pohlmann, Jan-Dag; Wysujack, Klaus (2023): Continuous thermosalinograph oceanography along RV METEOR cruise track M185 [dataset]. PANGAEA, <https://doi.org/10.1594/PANGAEA.960971>

ADCP:

Hanel, Reinhold; Kopte, Robert; Ferrer, Luis (2023): ADCP current measurements (38 kHz) during RV METEOR cruise M185 [dataset]. PANGAEA, <https://doi.org/10.1594/PANGAEA.956604>

EK80:

Proud, Roland; Rommel, Alix Claire Maria (2025): Raw EK80 echosounder narrowband data collected during RV Meteor cruise 'Assessing Oceanic Impacts on Arrival and Transport of European Eel Larvae' (M185) in 2022 [dataset]. PANGAEA, <https://doi.org/10.1594/PANGAEA.973496>

EDNA:

Environmental DNA (fish metabarcoding, Teleo marker): raw reads to be archived at NCBI SRA (submission in progress)

Cruise Report

M185: https://doi.org/10.48433/cr_m185

M186

Azores Hot Vents

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

J.C. Belo, C. Schmidt, M. Andrade, R. Zitoun, C. Hensen

Insitute of Geophysics, University of Hamburg | Hamburg, Germany

C. Hübscher

Faculty of Geosciences, University of Bremen | Bremen, Germany

N. Kaul

Department of Biology, University of Évora | Évora, Portugal

H. Adão

Department of Marine Sciences, The University of Texas at Austin | Austin, USA

M. Lever

The main goal of RV METEOR expedition M186 was to investigate fluid dynamics on the Azores Plateau and the volcanic activity of the Azores Archipelago in the Central North Atlantic. The work represents a systematic continuation of several expeditions in the region over the past decade (e. g. M113, M141/1, and M162). The magmatic plateau shows an ongoing seismic and volcanic activity. Although countless submarine intrusions and volcanic cones have been described in the region, only hints of hydrothermal fluid vents had been identified on the Azores Archipelago, and none yet in the deep-sea environment.

The targets of the expedition were the São Jorge Channel, where traces of hydrothermal fluids were previously detected (Schmidt et al. 2020); the Hirondelle Basin, where fluids with elevated Mg and SO₄ concentrations were detected during M141/1 (Schmidt et. al. 2019), and the Tydeman Fracture Zone (cf. Figure 1). The key purposes of the cruise were (i) to gain a better understanding of the driving mechanisms of those fluid vents, (ii) to unravel the geochemical and microbiological processes affecting the fluids, and (iii) to improve the data base for the regional tephrostratigraphy. To achieve the goals, we conducted systematic surveys at all three working areas, including gravity coring, heat-flow measurements, OFOS-observations, CTD-measurements, as well as 2D seismic surveys.

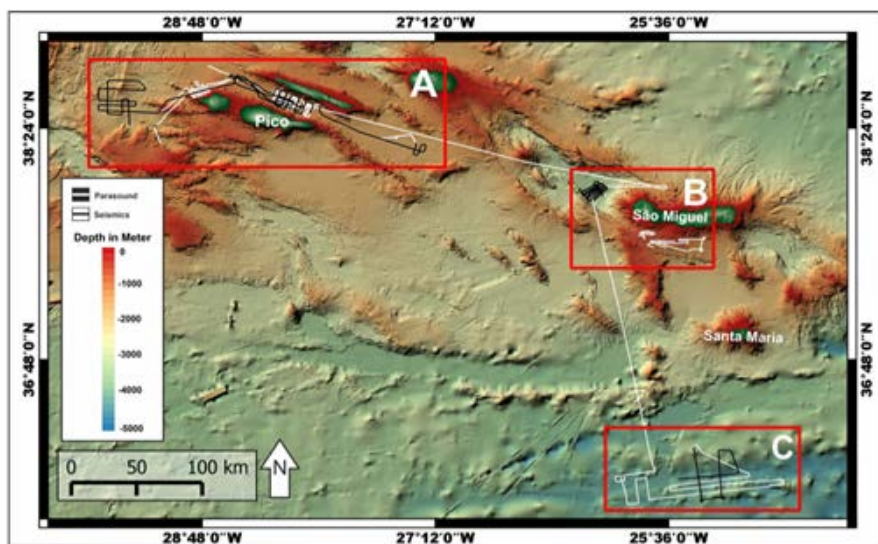


Figure 1: Bathymetric map of the three main working areas of cruise M186, white line shows the cruise track, black line represent seismic lines, red squares highlight the working areas A) São Jorge Channel, B) Hirondele Basin and C) Tydeman Fracture Zone.

Heat-flow transects and sites for gravity coring where typically placed on and across conspicuous seafloor features, such as dome structures or faults, often accompanied by blanking zones in the hydroacoustic record, which may, among other causes, indicate active upward fluid migration (Figure 2).

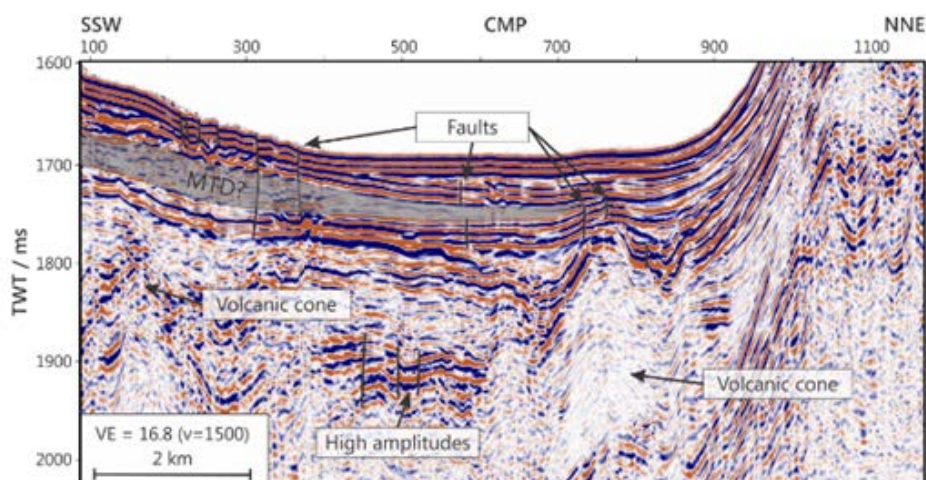


Figure 2: Exemplary seismic images from the São Jorge channel between the islands of São Jorge and Pico. Black lines indicate faults that cut the otherwise uniform deposition pattern. MTD: mass transport deposit; VE: vertical exaggeration.

During the cruise, two distinctly different types of porewater fluid signatures were identified in the gravity cores. Several of the gravity cores display a clear increase in total alkalinity with depth, whereas others show a pronounced decrease. Among all cores, M186-67-1-GC exhibits the lowest total alkalinity, reaching only 1.51 meq/L at 377 cm depth. This low alkalinity, in combination with decreasing sulfate and magnesium concentrations with depth, provides strong evidence for the presence of a hydrothermal component in the pore fluids within the São Jorge Channel. Such geochemical trends are characteristic of water-rock interaction at elevated temperatures, where sulfate is reduced and Mg is removed due to alteration reactions with basaltic material.

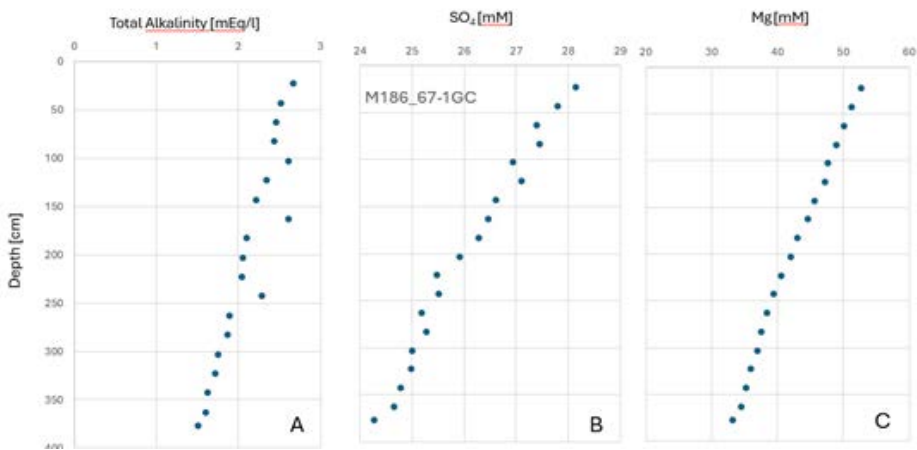


Figure 3: Exemplary gravity core of the São Jorge channel between the islands of São Jorge and Pico. A: Total Alkalinity; B sulfate and C Magnesium.

Despite these clear indications of hydrothermal influence in the sediments, no corresponding hydrothermal signal could be detected in the water column. Likewise, numerous OFOS dives across the gravity core locations revealed no visible signs of active venting, such as bubbling, particulate plumes, or hydrothermal precipitates. This discrepancy suggests that hydrothermal fluids are indeed present and widespread within the subsurface sediments, but do not manifest as focused, channelized flow at discrete vent sites. Instead, the discharge of hydrothermal fluids in this region of the Azores Plateau appears to be predominantly diffuse.

Diffuse hydrothermal flow implies that fluids percolate slowly through porous or fractured sediments without forming concentrated upflow zones. This type of fluid discharge is common in volcanic or tectonically active areas where permeability is high but not sufficiently focused to form well-defined vent structures. The alternation between high- and low-alkalinity porewater profiles observed across different cores, along with the contrasting depth trends of Mg, Ca, and SO₄, may

therefore reflect spatial variations in the proximity of each core to volcanic cones or subsurface heat sources. Such variations would influence the temperatures experienced by the circulating fluids, thereby shaping the extent of mineral alteration and the resulting chemical signatures.

Overall, the porewater data indicate a widespread but low-intensity hydrothermal system beneath the São Jorge Channel, characterized by diffuse discharge rather than focused venting. This interpretation is consistent with the absence of visible hydrothermal activity in the water column and highlights the complexity of fluid–rock interactions occurring within the sediments of the Azores Plateau.

In addition to the porewater evidence for diffuse hydrothermal circulation, further results from the cruise also highlight the dynamic volcanic and sedimentary environment of the Azores archipelago.

In total, Tephra layers in 33 gravity cores were described and sampled onboard. Based on visual core descriptions as well as smear slide observations and geochemistry of glass shards, we distinguished in a first approach primary tephra fall and flow deposits from reworked/volcaniclastic deposits. Major and trace element analysis of glass shards obtained by electron microprobe and Laser Ablation ICP-MS has been used to establish first correlations between cores and subaerially-exposed pyroclastic deposits from the surrounding islands (Pico, Faial, São Jorge). Initial age models for the cores have been implemented. Our work will provide a long-term marine tephra record for the central islands of the Azores, contributing to a more robust assessment of the archipelago's eruptive frequency and extending the record westward by building on the work presented in Schindlbeck-Belo et al. (under revision).

References

Schmidt C, Hensen C, Hübscher C, Wallmann K, Liebetrau V, Schmidt M, Kutterolf S & Hansteen TH, Geochemical characterization of deep-sea sediments of the Azores Plateau – From early diagenesis to hydrothermal activity, *Marine Geology* 2020, doi: 10.1016/j.margeo.2020.106291.

Schmidt C, Hensen C, Wallmann K, Liebetrau V, Tatzel M, Schurr S, Kutterolf S, Haffert L, Geilert S & Hübscher C, Origin of high Mg and SO₄ fluids in sediments of the Terceira Rift, Azores–indications for caminite dissolution in a waning hydrothermal system, *Geochemistry, Geophysics, Geosystems* 2019, doi: 10.1029/2019GC008525.

Schindlbeck-Belo JC, Andrade M, Kling J, Kutterolf S, Pimentel A, Lebas E, Freundt A, Pank K, Hansteen TH, under revision, Facies characterization and volcanic source assignment of marine tephra deposits around São Miguel Island, Azores Archipelago: Geochemistry, Geophysics, Geosystems.

Scientific Output

Data

Event List:

<https://www.pangaea.de/expeditions/events/M186>

Pore water geochemistry data:

<https://osis.geomar.de/app/expeditions/361065>

Heat Flow:

<https://doi.pangaea.de/10.1594/PANGAEA.959620>

Cruise Report

M186: https://doi.org/10.48433/cr_m186

M186/2

AtlanTIC – Atlantic Trophic Interactions & Carbon Cycle

Authors

University of Bremen, FB 02, BreMarE – Bremen Marine Ecology | Bremen, Germany
H. Auel

University of Hamburg, IMF – Institute of Marine Ecosystem and Fishery Science | Hamburg, Germany
R. Koppelman, B. Martin

Productivity, Trophic Interactions and Functional Biodiversity of Pelagic Communities throughout the Atlantic Ocean and their impact on the Carbon Cycle

The AtlanTIC project, “Atlantic Trophic Interactions & Carbon Cycle: Productivity, Trophic Interactions and Functional Biodiversity of Pelagic Communities Throughout the Atlantic Ocean and Their Impact on the Carbon Cycle” used the transfer voyage M186/2 of the research vessel R/V METEOR for a joint research and training initiative of the Universities of Bremen and Hamburg. Pelagic biodiversity, productivity and trophic interactions were studied along the cruise track covering different hydrographic regimes and biogeographic provinces throughout the subtropical and tropical Eastern Atlantic Ocean. The cruise track extended from the Canary Islands (northern sub-tropical Atlantic in winter) via tropical waters and the southern sub-tropical Atlantic during austral summer to regions affected by the Benguela Current upwelling system off Namibia. We studied how differences in pelagic community structure, functional biodiversity, biological productivity, and trophic interactions affect ecosystem functioning. The second major aim of AtlanTIC was student training for the Universities of Bremen and Hamburg in state-of-the-art methods in marine research. The cruise offered a unique opportunity for hands-on training in an interdisciplinary setting.

At each station, we deployed a CTD sensor connected to a rosette water sampler in order to measure depth profiles of temperature, salinity, dissolved oxygen

concentration, light, and chlorophyll fluorescence. On the way back to the surface, we collected water samples from discrete depth layers. In addition, we deployed several plankton nets with different mouth openings and mesh sizes in order to sample different plankton size classes from unicellular phytoplankton algae to small zooplankton animals in the millimetre- to centimetre-scale. Our largest net, the Isaacs-Kidd Midwater Trawl (IKMT) with a mouth opening of seven square metres and 4.5 mm mesh size was towed behind the vessel and caught larger crustaceans and small mesopelagic fishes.

The University of Hamburg recorded and analyzed oceanographic parameters such as temperature and salinity on the R/V METEOR's transit route from Las Palmas, Spain, to Walvis Bay, Namibia. Along the route from the North to the South Atlantic, chlorophyll measurements and estimates of phytoplankton primary production were conducted directly on board. A special fluorometer (FastTracka, Chelsea Technologies) was used to measure the physiological fitness of the phytoplankton. Water samples were collected to characterize the phytoplankton community. Depth-stratified Multinet catches to determine the regional and vertical distribution of microplankton were successfully conducted and supplemented with Apstein net catches. These samples were used to analyze differences in functional biodiversity, productivity, and trophic interactions within pelagic communities in different biogeographic provinces (North Atlantic Subtropical Gyre, Eastern Tropical Atlantic, and South Atlantic Gyre).

The University of Bremen deployed a Hydrobios MultiNet Midi (mouth area 0.25 m²) to collect mesozooplankton in the standard depth intervals of 0–50, 50–100, 100–200, 200–400 and 400–600 m. At two stations, we sampled down to 1500 m with depth intervals of 0–50, 50–200, 200–600, 600–1000 and 1000–1500 m. Preliminary results showed that there were differences in species distribution and productivity along the cruise with a dominance of copepods. In the northern part of the study area, the herbivorous copepod *Undinula* occurred regularly in high abundance. Samples from the two stations sampled down to 1500 m contained many dead copepods that might form a substantial part of the export flux by the biological carbon pump. An unexpected finding was a high abundance of likely diapausal *Calanoides natalis* at the second station within the deepest depth interval of 400–600 m. A more detailed analysis in the home lab showed that zooplankton abundance was higher in the subtropical South Atlantic than in the subtropical North Atlantic. Total zooplankton abundance decreased with increasing depth. A total of 69 different mesozooplankton taxa were identified. Copepods were the dominant group throughout the water column at each station, with 33 copepod taxa identified. Biodiversity was highest near the equator and decreased towards subtropical waters. Clausocalanidae and the cyclopoid genus *Oithona* dominated in the upper 100 m at all stations, whereas *Oncaea* became more dominant towards the mesopelagic layer.

The analysis of data and samples of cruise leg M186/2 is not finished yet. They form part of the basis of the ongoing BMFTR project IMAPP – “Integrative Mapping of Atlantic Protection Areas” focusing on the identification of areas suitable as potential offshore marine protected areas in the context of the new United Nations BBNJ agreement on biodiversity in regions beyond national jurisdiction.

Scientific Output

List of Publications

Linke CM, Biodiversity and distribution of zooplankton in the central Atlantic, 2024, BSc thesis, University of Bremen.

Schottes J, A comparison of phytoplankton composition and abundance with chlorophyll-a off the African Coast, 2024, Project study, University of Hamburg.

Schottes J, Microplankton abundance and diversity along a north-south transect through the Atlantic Ocean, 2025, MSc thesis, University of Hamburg.

Data

Auel H (2023) Master tracks in different resolutions of METEOR cruise M186/2, Las Palmas – Walvis Bay, 2023-01-03–2023-01-22:
<https://doi.org/10.1594/PANGAEA.959132>

Auel H (2023) Master track of METEOR cruise M186/2 in 1 sec resolution (zipped, 11.1 MB):
<https://doi.org/10.1594/PANGAEA.959131>

Auel H, Schlundt M, Herrford J (2023) Continuous thermosalinograph oceanography along RV METEOR cruise track M186/2:
<https://doi.org/10.1594/PANGAEA.960974>

Kopte R, Koppelman R, Auel H (2023) ADCP current measurements (38 kHz) during RV METEOR cruise M186/2:
<https://doi.org/10.1594/PANGAEA.961671>

Public relations and outreach

Die schwimmende Universität. Centrum für Erdsystemforschung und Nachhaltigkeit (CEN), Universität Hamburg:
<https://www.cen.uni-hamburg.de/about-cen/news/08-news-2023/2023-02-08-meteor-reise.html>

Cruise Report

M186/2: https://doi.org/10.48433/cr_m186_2

Biogeochemical dynamics of upwelling filaments in the Benguela

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

T.J. Browning, E.P. Achterberg

Introduction

Upwelled waters off Benguela (Southeast Atlantic) bring cool waters and elevated concentrations of nutrients to the sunlit surface. This results in very high primary productivity, which contrasts strongly with the adjacent warmer, low nutrient, lower productivity waters of the South Atlantic Subtropical Gyre. Upwelled waters of the Benguela both (i) flow northwards as part of the main Benguela Current, and (ii) are channelled into westward (offshore) flowing filaments (Mohrholz et al., 2014). Upwelled filaments, distinguished by their colder temperatures, often show offshore velocities of up to 30 cm s^{-1} , have meridional extents of tens of km, depths of 50–100 m, can reach extents of 1000 km offshore, and constitute the major mechanism for offshore transport of upwelled water (Hösen et al., 2016). Offshore flowing upwelling filaments in the Benguela are mainly focussed north west of Lüderitz (24–26°S).

On moving offshore, filament waters warm and nutrient concentrations are drawn down and this probably results in shifts in available forms of nutrients, changes in microbial community composition, and altered sinking particle export. For instance, prior experiments in the region (Browning et al., 2017) showed that phytoplankton nutrient limitation displayed a broadscale shift from iron limitation in the upwelling zone to nitrogen-iron co-limitation in the upwelling-subtropical gyre transition zone. The iron limitation in the upwelling zone is driven by upwelled waters having a higher ratio of nitrogen than iron in comparison to phytoplankton requirements, with iron recycling and enhanced aerosol supplies leading to nitrogen (nitrate) drawdown further offshore. Similar changes might therefore be hypothesized along Benguela filaments.

On this research cruise we tracked two filaments and undertook detailed investigations to investigate biogeochemical changes along them. Key questions we addressed were:

1. Where do the boundaries in N limitation, Fe limitation, and N-Fe co-limitation occur and are these accurately predicted by the dissolved concentrations of these nutrients?
2. How do concentrations and speciation of nutrients and micronutrients vary with age and mixing following deep (200–300 m) upwelling of waters enriched in inorganic nutrients and micronutrients? Does phytoplankton diversity scale with nutrient heterogeneity? Are waters with high phytoplankton and nutrient diversity characterized by N-Fe co-limitation of phytoplankton growth?
3. Do aerosols from the African continent significantly alter nutrient budgets of upwelled filaments as they are advected offshore?
4. What is the fate of nutrients and micronutrients transported to the surface in upwelling filaments? Specifically, what is the fraction of utilized vs. unutilized (subducted) nutrients? What is the nutrient supply flux from filaments to the subtropical gyre?
5. Do different nutrient limitation provinces coincide with altered modes of carbon and major nutrient export to the deeper ocean?

Methods

On the M187 research cruise (25.01.2023–04.03.2023; Walvis Bay – Walvis Bay), two filaments were successfully mapped from cold water upwelling sites near or over the Namibian shelf through to warmer waters offshore. Filaments were identified and tracked via a combination of satellite images (sea surface temperature and chlorophyll-a), shipboard thermo-salinograph and ADCP measurements, as well as drifting buoy deployments. This was followed by a transect of twelve stations outwards into the subtropical gyre, reaching a maximum westward position of 5 °W. Sampling stations were conducted to a maximum depth of 1000 m and involved an array of deployments to investigate the biogeochemistry of the water column. One station was occupied within the filament each day and the following deployments were carried out: regular CTD (two with one focussing on the near surface and one at greater depths), trace-metal-clean Go-Flo bottle deployments, in situ pump deployment, water column light measurements. Regular CTD sampling was undertaken for non-contamination prone samples (macronutrients, salinity, phytoplankton pigments and photophysiology, microbial genomics, flow cytometry, particulate

organic carbon, nitrogen and silica, nitrogen and carbon fixation) as well as gas measurements (oxygen and DIC). Go-Flo bottle sampling was used for trace elements. In situ pumps were used for Th-234 activity measurements and radium (via flow over manganese cartridges). Nutrient addition bioassay experiments were conducted throughout the research cruise to assess the nutrients (co-) limiting to phytoplankton growth. Upon completion of the daily, depth-resolved sampling station, we then sailed in a zig-zag manner across the filament, sampling underway, to map surface biogeochemistry of the filament. A towed water sampling device was used to allow for collection of water samples at ca. 2–3m depth without trace metal contamination. Aerosol collection and observations of ocean colour (via hyperspectral radiometry) were undertaken continuously.

Results and Discussion

Upwelled waters in the Benguela and within the filaments had elevated concentrations of macronutrients (nitrate, phosphate, silicic acid), elevated chlorophyll and particulate organic carbon, and diatom-dominated phytoplankton communities. For example, nitrate and chlorophyll-a concentrations were enhanced up to 100 and 10-fold, respectively, in filaments compared to surrounding waters. The micronutrient iron was found to be the nutrient limiting phytoplankton growth. On moving offshore filament temperatures increased, macronutrient and phytoplankton concentrations declined and phytoplankton communities became dominated by a more mixed community of diatoms, haptophytes and cyanobacteria. Phytoplankton nutrient limitation remained iron limited (excess nitrate was still present) but showed evidence for serial limitation by nitrogen, that is supplying iron to phytoplankton increased phytoplankton growth to some extent but this was enhanced by supplying nitrogen and iron. Rates of primary production were elevated in filaments, whereas rates of nitrogen fixation were low and increased at the filament boundaries. Subtropical gyre waters hosted depleted macronutrient and phytoplankton concentrations and phytoplankton communities that were dominated by cyanobacteria. Phytoplankton growth was either co-limited by nitrogen and iron or showed serial nitrogen-iron limitation (i. e., nitrogen being the primary limiting nutrient, followed by iron). Nutrient and chlorophyll-a transports from the upwelling zone to the gyre via the filaments were strongly elevated (Nicholas et al., in review). Specifically, filaments were calculated to transport up to 2.5×10^3 tonnes of nitrogen and 40 tonnes of chlorophyll-a per day from the upwelling zone towards the subtropical gyre. Integration over multiple filaments throughout the Benguela upwelling zone suggests that filaments represent one of the major sources of new nutrients sustaining productivity in the South Atlantic Gyre. Sinking particle fluxes of elements (including carbon) were substantially elevated in the upwelling zone and the filaments in comparison to the subtropical gyre. Hyperspectral radiometry measurements showed major transitions between the upwelling zone and

filaments and the subtropical gyre that was linked to the nutrient limitation status of the dominant phytoplankton communities (Browning et al., 2023; Robinson et al., in review). Overall filaments acted as strong CO₂ sources due to outgassing from the upwelled water, with surrounding waters acting as a CO₂ sink (Qiu et al., in review).

Analysis of a range of samples remains underway (microbial genomics, flow cytometry, radium) and will allow for the full picture of biogeochemical changes along filaments to be established.

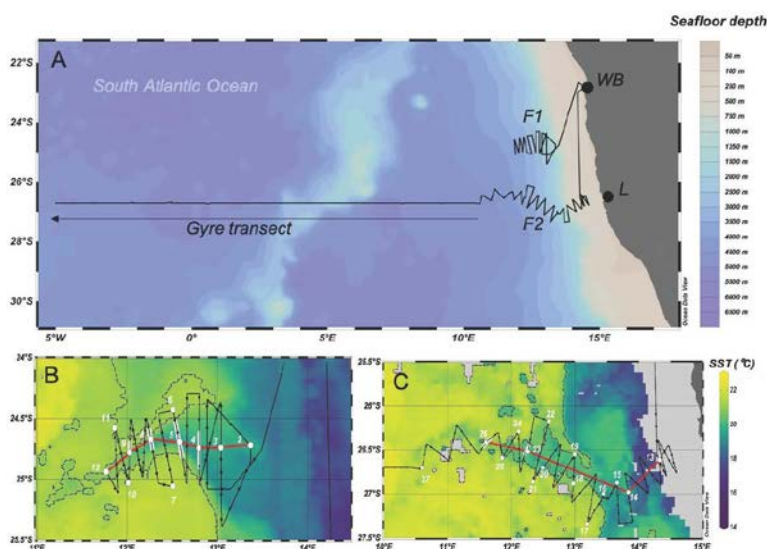


Figure 1. Map of sampling sites on M187. (a) Overall locations identifying the two filaments (F1 and F2) investigated alongside the gyre transect. WB = Walvis Bay; L = Luderitz. (b) Merged satellite derived SST (8-day composite data) 25.01 to 1.02.2023. (c) merged satellite derived SST (8-day composite data) 10.02 to 17.02.2023. Dotted blue line: 20.41°C SST threshold used to determine the contours of the filament. Black lines: ship trajectory, black points: surface underway sampling stations, numbered white points: CTD stations, red lines: transects connecting stations determined post-cruise to fall within the filaments, white lines: sections used for volume transport calculations (discussed in the text).

References

Browning TJ, et al., Nutrient co-limitation at the boundary of an oceanic gyre', Nature 2017, 551, 242–246, doi: <https://doi.org/10.1038/nature24063>.

Browning TJ, Saito MA, Garaba SP, Wang X, Achterberg EP, Moore CM, Engel A, McIlvin MR, Moran D, Voss D & Zielinski O, Persistent equatorial Pacific iron limitation under ENSO forcing, Nature 2023, 7978, 330–335, doi: <https://doi.org/10.1038/s41586-023-06439-0>.

Hösen E, et al., Scales and properties of cold filaments in the Benguela upwelling system off Lüderitz, *Journal of Geophysical Research: Oceans* 2016, 121, 1896–1913, doi: <https://doi.org/10.1002/2015JC011411>.

Mohrholz V, et al., Cross shelf hydrographic and hydrochemical conditions and their short term variability at the northern Benguela during a normal upwelling season, *Journal of Marine Systems* 2014, 140, 92–110 doi: <https://doi.org/10.1016/j.jmarsys.2014.04.019>.

Scientific Output

List of Publications

Nicolas A, Cardoso C, Liu H, Calil P, Dengler M, Achterberg EP & Browning TJ, Benguela upwelling filaments shape biogeochemical distributions and are a major pathway of new nutrients to the South Atlantic Subtropical Gyre, *Journal of Geophysical Research (Biogeochemistry)*, in review.

Qiu L, Hu Z, Esposito M, Browning TJ, Voß D, Li Q & Achterberg EP, Spatial Variability and Biogeochemical Implications of Seawater Carbonate Chemistry in an Upwelling Filament of the Benguela Upwelling System from High-Resolution Underway Measurements, *Global Biogeochemical Cycles*, in review.

Robinson TB, Liu H, Garaba SP, Voss D, Schuback N, Moore CM, Oxborough K, Achterberg EP & Browning TJ, Nutrient limitation regimes control sunlight-stimulated chlorophyll fluorescence in the South Atlantic Ocean, *Communications Earth and Environment*, in review.

List of conference presentations

2026 | **Sun-induced chlorophyll fluorescence as a window into phytoplankton nutrient stress: Evidence from the Benguela and South Atlantic.** Ocean Sciences Meeting, Glasgow, United Kingdom

Data

Continuous thermosalinograph data:
<https://doi.org/10.1594/PANGAEA.962927>

Shipboard 75 kHz ADCP measurements:
<https://doi.org/10.1594/PANGAEA.962913>

Shipboard 38 kHz ADCP measurements:
<https://doi.org/10.1594/PANGAEA.962912>

Above water radiometry data:
<https://doi.org/10.1594/PANGAEA.973430>

Downwelling irradiance data:
<https://doi.org/10.1594/PANGAEA.973426>

Carbonate chemistry:
<https://doi.pangaea.de/10.1594/PANGAEA.984417>

Optical water quality variables:
<https://doi.org/10.1594/PANGAEA.959668>

Cruise Report

M187: https://doi.org/10.48433/cr_m187

M189

Benguela Niños: Physical Processes in Upwelling Regions and Long-Term Variability

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

M. Dengler, P. Brandt, M. Körner, R. A. Imbol Koungue, et al.

Leibniz Institute for Baltic Sea Research Warnemünde | Warnemünde, Germany

V. Mohrholz, D. L. Arévalo Martínez, J. Söder

The objective of the physical – biogeochemical measurement program during R/V METEOR cruise M189/1 (April 16–May 13, 2023, Walvis Bay – Walvis Bay, Namibia) was to measure the variability of the circulation and the coastal upwelling off Angola and Namibia and elucidate the processes relevant to coastal upwelling, greenhouse gas production and emission, and biological productivity. The aims of the cruise were to *i.* continue, based on previous programs, enhancing the ocean observing system off Southwest Africa aimed at studying the eastern boundary upwelling variability on time scales from subseasonal to decadal; *ii.* investigate processes relevant for upwelling variability and its consequences for biological productivity; *iii.* synthesize high-resolution simulations, remote sensing, and in-situ observations to understand the development of Benguela Niño events; *iv.* investigate the impact of the changing southeastern tropical Atlantic Ocean mean state on Benguela Niño events with respect to their frequency, strength, location and impacts as well as their predictability; *v.* resolve the microbial nitrogen and sulfur cycles in order to constrain the variability of nitrogen and sulfur turnover in the Benguela upwelling system.

The measurements conducted during cruise M189/1 formed part of a long-term observational program in the tropical eastern South Atlantic. This program includes moored observations of velocity, hydrography, and oxygen off Angola (11°S) and Namibia (23°S), as well as repeated hydrographic and upper-ocean turbulence surveys along selected sections in the territorial waters of both coastal states. The sites had previously been maintained and sampled during R/V *Meteor* cruises M98, M120, M131, M148, M158, and M181.

Physical control of primary production in the tropical Angolan upwelling system

The combined data set collected in the tropical Angolan upwelling region allowed major advancements in the understanding of the physical processes that control upwelling and primary productivity (Körner et al., 2024a). The strength and seasonality of upwelling and productivity in eastern boundary upwelling systems are usually related to local wind forcing. However, in the tropical upwelling system off Angola, seasonal maxima of productivity occur when upwelling favorable winds are weak. In Körner et al., 2024a, we show that in the seasonal productivity maximum here is due to the combined effect of coastal trapped waves and elevated tidal mixing on the shelf. During the upwelling season in austral winter, the passage of an upwelling coastal trapped wave (CTW) displaces the nitracline upward by more than 50 m (Figure 1). Thereby, nitrate-rich waters spread onto the shelf, where elevated vertical mixing causes a nitrate flux into the surface mixed layer and fuels growth of phytoplankton.

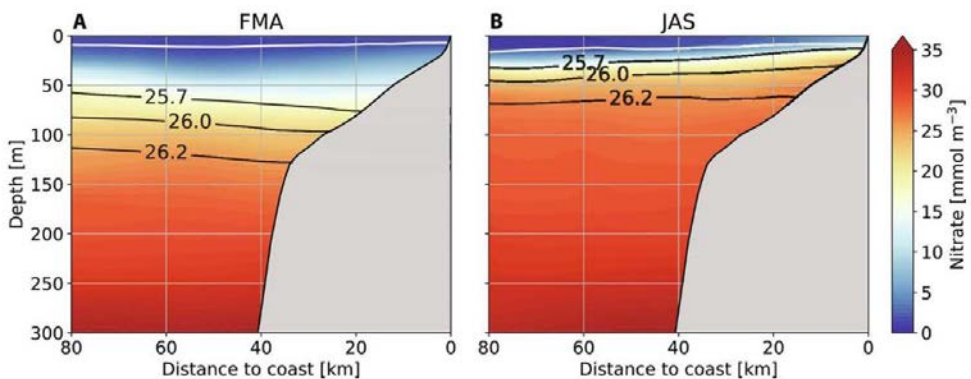


Figure 1: Cross-shelf sections of inferred nitrate concentration as a function of distance to the coast. Data collected between 10°S and 12°S are projected onto the mean topography in this latitude band. (a) shows the mean section during non-upwelling in February–April and (b) during the upwelling season in July–September. Black lines show selected isolines of the mean potential density field (from Körner et al., 2024a).

CTWs observed at the continental slope off Angola are often remotely forced at the equator. Zonal wind fluctuations at the equator excite equatorial Kelvin waves which propagate eastward. Upon reaching the eastern boundary part of their energy is transformed into westward propagating Rossby waves and part of it is transformed into poleward propagating CTWs.

In austral winter, CTWs of different vertical structure propagate along the Angolan shelf. First low-mode CTWs visible in sea level anomaly (SLA) data arrive in the tAUS (Figure 2). Subsequently, slower high-mode CTWs are observed, which

displace the depth of the nitracline upward. These high-mode CTWs are phase-locked to the low-mode CTWs visible in SLA. The strength of the low-mode CTWs is correlated with the strength in primary production peaking more than a month after the SLA minimum.

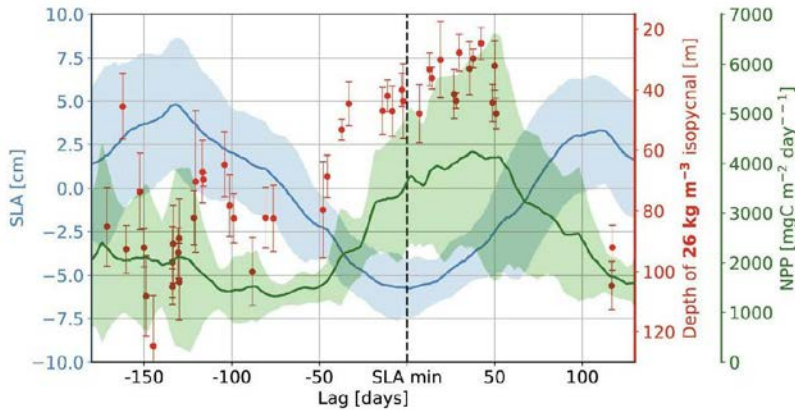


Figure 2: Sea level anomaly (SLA), net primary production (NPP), and depth of 26 kg m^{-3} isopycnal as a function of time lag (days) with respect to the time of the annual minimum in SLA occurring during the main upwelling season. Blue line shows the mean SLA for 1995–2022. The timing of the annual SLA minimum is determined using the SLA time series treated with a low-pass filter (cutoff period of 135 days). Green line shows the mean NPP for 2002–2021. Shaded areas show the standard deviation. Red dots indicate the depth of the respective potential density surface averaged for each cruise considering all CTD profiles taken between 250- and 1000-m water depth. Red bars indicate the SD of the depth of the density surface. Data between 10°S and 12°S are used for all three variables (from Körner et al., 2024a).

Strength and timing of austral winter Angolan coastal upwelling

Interannual variability of the productivity maximum in the tropical Angolan Upwelling region is strongly correlated to the amplitude of the upwelling CTW as seen in sea level data. Given that CTWs are connected to equatorial forcing, a predictability of the strength of the productivity maximum is suggested.

The year-to-year variability in the timing and amplitude of the austral winter upwelling CTW was analysed by examining sea surface temperature, sea level anomaly, and wind fields (Körner et al., 2024b). The results show that the timing of the CTW is influenced by variability in the equatorial region and along the southern African coast. Weaker equatorial easterlies from April to July delay the generation of the upwelling Kelvin wave, leading to a later arrival of the upwelling CTW. In contrast, the amplitude of the CTW is primarily influenced by variability in the eastern equatorial Atlantic and the central South Atlantic, where the South Atlantic Anticyclone is located. A cooling in the eastern equatorial Atlantic three to four months before the arrival of the CTW causes stronger zonal winds, ultimately

leading to a stronger austral winter upwelling CTW (Figure 3). Our results suggest that the timing and amplitude of the upwelling CTW in the tropical Angolan upwelling region during austral winter are predictable on seasonal time scales.

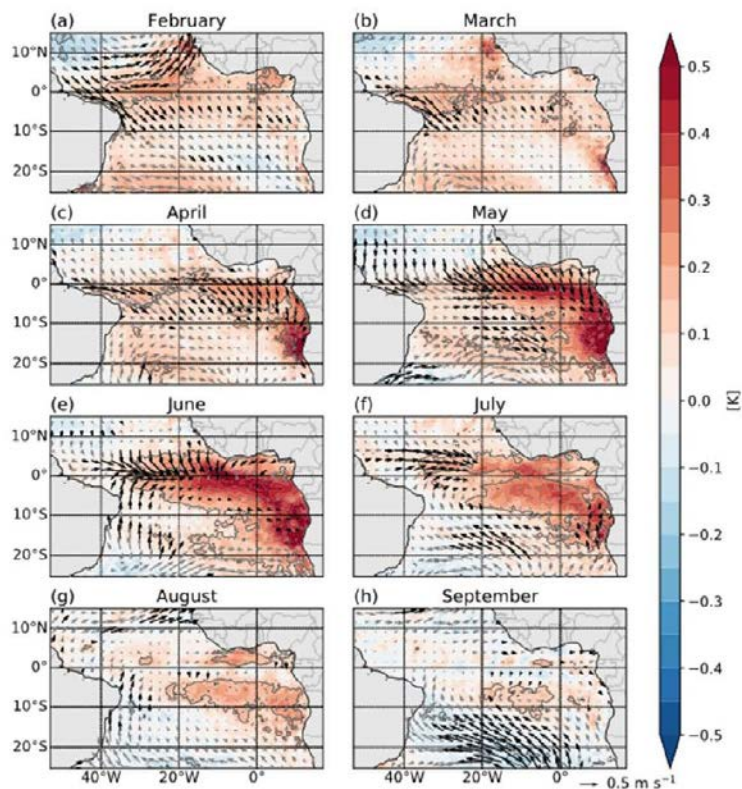


Figure 3: Maps showing the regression slopes of SST (color) and wind (arrows) onto the timing of the SLA minimum in the tAUS. Regression are calculated separately for the different months from February to September. Significant correlation (95% confidence level) between the timing and SLA and the timing and winds are marked by grey lines and black arrows (from Körner et al., 2024b).

Drivers and impact of the 2021 extreme warm event in the Tropical Angolan upwelling system

Benguela Niños are extreme warm events that typically occur during the main downwelling season (austral fall) in the tropical Angolan upwelling system when the biological productivity is low. However, the extreme warm event that occurred between April and August 2021 stands out due to its late timing. It occurred and peaked during the main upwelling season in austral winter with sea surface temperature anomalies exceeding 2°C in the Angola-Benguela area in June 2021 (Imbol Koungue et al., 2024). This led to an unprecedented reduction of the net

primary production off southern Angola. Both local atmospheric processes and remote influences (via downwelling coastal trapped wave propagations) have contributed to the onset of the extreme warm event in April and its intensification towards the peak phase in June. Moreover, the poleward advection of warm equatorial waters toward the Angola-Benguela area in May 2021 might have contributed to the warming, since the transport of the Angola Current, as estimated from observations, was notably elevated.

Scientific Output

List of Publications

Körner M, Brandt P & Dengler M, Strength and timing of austral winter Angolan coastal upwelling, Scientific Report 2024b, 14, 27400, doi: 10.1038/s41598-024-77917-2.

Imbol Koungue RA, Brandt P, Prigent A, Aroucha LC, Lübbecke J, Imbol Nkwinkwa A SN, Dengler M & Keenlyside N, Drivers and impact of the 2021 extreme warm event in the tropical Angolan upwelling system, Scientific report 2024, 14, 16824, doi: 10.1038/s41598-024-67569-7.

Körner M, Brandt P, Illig S, Dengler M, Subramaniam A, Bachèlery M-L & Krahmann G, Coastal trapped waves and tidal mixing control primary production in the tropical Angolan upwelling system, Science Advances 2024a, 10 (4), eadj6686, doi: 10.1126/sciadv.adj6686.

Kopte R, Becker M, Fischer T, Brandt P, Krahmann G, Betz M, Faber C, Winter C, Karstensen J & Wiemer G, FAIR ADCP data with OSADCP: a workflow to process ocean current data from vessel-mounted ADCPs, Frontiers in Marine Science 2024, 11, 1425086, doi: 10.3389/fmars.2024.1425086.

Theses:

Körner M, Physical drivers of seasonal variability in the tropical Angolan upwelling system, 2024, PhD thesis, Christian-Albrechts-Universität zu Kiel, 129 pp.

Fiedler B, Characteristics and onshore transport of non-linear internal waves in the Angolan upwelling region, 2024, BSc thesis, Christian-Albrechts-Universität zu Kiel, 36 pp.

List of conference presentations

2025 | **Physical processes and biological productivity in the upwelling regions of the tropical Atlantic**, Pan-CLIVAR Meeting, Bali, Indonesia

2024 | **Tropical upwelling systems**, GEOMAR-IOW Workshop, IOW, Warnemünde, Germany

2024 | **Coastal Trapped Waves and Tidal Mixing Control Primary Production in Angolan Upwelling**, Gordon Research Conference on Ocean Mixing, South Hadley, Massachusetts, United States

Data

Physical oceanography

Conductivity, temperature, depth profile data (CTD):

<https://osis.geomar.de/app/expeditions/361075/files?name=M189>

ADCP current measurements (38kHz):

<https://doi.org/10.1594/PANGAEA.962915>

ADCP current measurements (75kHz):

<https://doi.org/10.1594/PANGAEA.962916>

Underway thermosalinograph data (S, T):

<https://doi.pangaea.de/10.1594/PANGAEA.958394>

Mooring data from KPO_1246 (velocity, T, and oxygen records):

<https://osis.geomar.de/app/expeditions/361075/files?name=M189>

Mooring data from short term deployments KPO 1273 (200m), KPO 1274 (100m) and KPO 1275 (50m) (velocity, T, and oxygen records):

<https://osis.geomar.de/app/expeditions/361075/files?name=M189>

Multibeam bathymetry raw data:

<https://doi.org/10.1594/PANGAEA.965762>

Chemical Oceanography

Oxygen concentration from water samples:

<https://osis.geomar.de/app/expeditions/361075/files?name=M189>

Nutrient concentrations from water samples:

<https://osis.geomar.de/app/expeditions/361075/files?name=M189>

Cruise Report

M189: https://doi.org/10.48433/cr_m189_1

M190

Distribution of Venting Along the Mid-Atlantic Ridge (29–38°N) and Implications for Hydrothermal Exchange and Vent Ecosystems

Authors

University of Bremen, MARUM – Center for Marine Environmental Sciences | Bremen, Germany

W. Bach, A. Diehl, J. Kleint, F. Schubotz, M. Walter

Constructor University Bremen | Bremen, Germany

A. Koschinsky, E. Meckel, L. Klose

Max-Planck Institute for Marine Microbiology | Bremen, Germany

A. Meyerdierks, C. Borowski, N. Dubilier

Federal Institute for Geosciences and Natural Resources | Germany

C. Ostertag-Henning

University of Lyon | France

I. Daniel

University of Münster | Münster, Germany

H. Strauss

University of Göttingen | Göttingen, Germany

E. Runge

Summary

Cruise M190 of RV *Meteor* was carried out in order to be able to take geochemical and biological samples at hydrothermal vents on the Mid-Atlantic Ridge between 29°10'N and 38°20'N. The springs in this area are characterized by very different geological settings, and the fluids are correspondingly very different in nature. The hydrothermal vents were sampled with the ROV MARUM Quest 4000 to determine the material differences between the individual vents and to place

them in relation to the geological framework. We also wanted to investigate how the distribution and composition of the sources affect the genetic and metabolic diversity of symbiotic and free-living microorganisms. Surveying and sampling the water column and subsequent geochemical analyses will reveal how metals are introduced into the ocean and how their binding modes change. Extensive sampling and investigation of diffuse sources will provide insight into the activity of intracrustal microorganisms and their metabolic strategies. A total of 12 dives with the ROV MARUM Quest 4000m and eleven CTD stations, five of them combined with deep-sea pumping, provided sufficient samples to address the scientific questions.

Aims of the Cruise

The major aims of cruise M190 of R/V Meteor was highly coordinated sampling of their fluids, rocks, and biota, as part of our joint geo-bio interface studies in the Research Area 'Ocean Floor as a Reactor' of the proposed Cluster of Excellence "The Ocean Floor – Earth's Uncharted Interface". The cruise track is shown in Figure 1. The hydrothermal vents in the area of the Mid-Atlantic Ridge (MAR) between 29°10'N and 37°50'N occur in different geological settings (axial volcano vs. detachment fault vs. axial volcanic ridge) and are hence geochemically highly diverse. Sampling hydrothermal vents with ROV MARUM Quest 4000 allowed us to assess the diversity of the hydrothermal fluids between those km-spaced vents and determine the volcanic and faulting controls of this diversity. We also wanted to examine how the distribution of vents and variability of fluid compositions affect the genetic and metabolic diversity of symbiotic and free-living microbes. We also wanted to conduct comprehensively sampling and analyses of diffuse fluids to assess activity and pathways of subseafloor microbial metabolism.

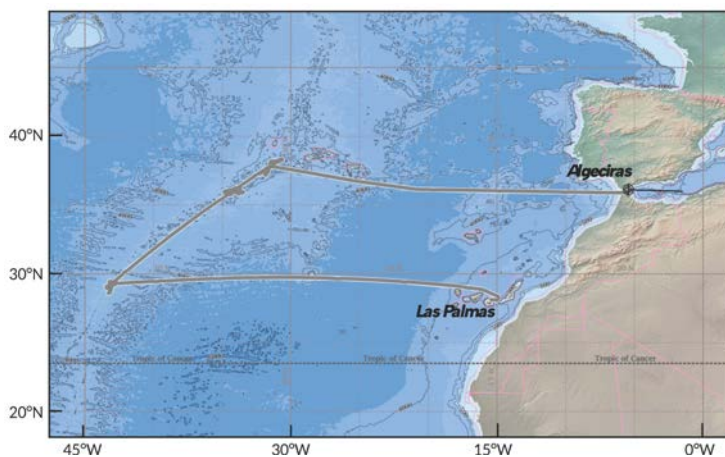


Figure 1: Cruise track of expedition M190.

Summary of ROV QUEST Dives

A series of twelve ROV dives were conducted during Expedition M190 to explore and sample hydrothermal vent systems along the Mid-Atlantic Ridge, including the Broken Spur, Rainbow, Lucky Strike (Ewan field), and Menez Gwen vent fields. The primary objectives were to collect hydrothermal fluids, rocks, and biota, and to deploy/recover in-situ instruments.

The first three dives at the **Broken Spur** vent field focused on characterizing active chimneys, diffuse venting, and faunal assemblages. Dive 468 revealed extensive fluid venting and shrimp-dominated fauna. Fluids up to 320°C were observed, and multiple fluid, rock, and filter samples were collected at two vent sites. Dive 469 collected high-temperature fluids, biota (including mussels), and sulfide material from three different vent clusters. Dive 470 focused on the Triple Chimney complex, sampling black smoker fluids up to 368°C and recovering sulfide talus and metabolite catchers deployed earlier.

The following five dives took place in the **Rainbow** area. Dive 471 deployed long-term observatory equipment and temperature probes around the Rainbow Pits and sampled mussel beds at diffuse vents (up to 96°C). Dive 472 collected fluids, rocks, clams, bacterial mats, and mussels at the Pits site. Dive 473 explored hilly terrain at the massif base, retrieving various mineralized and veined rocks, oxide crusts, and biological samples (sponges and biofilms). Dive 474, at the main Rainbow vent field, located multiple active chimneys with mussels. Fluids up to 142°C and diffuse vents were sampled, and associated chimney fragments and mussels were collected. Dive 475 targeted high-temperature smokers (up to 376°C) on a prominent sulfide mound, obtaining fluid samples with both KIPS and Major samplers. Additional diffuse venting (230°C) and mussel habitats were also sampled.

Dive 476 at the **Ewan** diffuse vent field surveyed extensive mussel beds along talus slopes and graben bases. Diffuse fluids (16–26°C) were sampled alongside mussel, rock, and bacterial mat collections. Despite strong flow, temperatures remained below 30°C, confirming low-temperature venting. Multiple fluid and biota samples were obtained, with ISMS analyses conducted in situ.

Two of the remaining dives explored the **Menez Gwen** vent field (Azor Ana, White Flames, Woody, and Cage sites). High-temperature vent fluids (up to 298°C) and diffuse flow sites (45–107°C) were sampled along with chimney fragments, mussel scoops, and microbial mats. Metabolite catchers were deployed and recovered. Dive 478 investigated the nearby Bubbylon field, sampling vent fluids up to 301°C, gas-emitting chimneys, and diffuse flow zones at Fontenuova. Biological and rock samples were collected from multiple active and inactive structures.

Fluid and Rock Sampling

High-temperature and diffuse fluids were systematically sampled using KIPS (Kiel Pumping System), titanium syringe “Major” samplers, and Niskin bottles mounted on ROV *MARUM QUEST*. An *in situ* mass spectrometer (ISMS) was operated to measure dissolved gas concentrations before sampling.

KIPS collected 27 samples across all vent fields, with recorded temperatures ranging from diffuse 6 °C up to 370 °C, including 368 °C at Broken Spur and 366 °C at Rainbow. The Major samplers, consisting of two titanium syringes, were used primarily for very hot vent fluids. Without built-in thermometers, they were operated alongside KIPS or prior temperature measurements. Samples were collected directly from vent orifices and processed immediately on deck for gas analyses (H_2 , CH_4). Niskin bottles (5 L each) were closed within the vent plumes at 1–5 m above orifices to collect dispersing fluids for trace metal and He isotope analyses.

Forty-nine rock samples (sulfides, basalts, breccias, and anhydrite chimneys) were collected using the ROV manipulator and stored in onboard bins. Samples from Broken Spur were mostly oxidized sulfide chimneys; Rainbow yielded silicified carbonates and polymetallic sulfide chimneys; Lucky Strike produced fresh basalts; and Menez Gwen and Bubblylon featured anhydrite-barite chimneys and vesicular basalts.

First Results

Fluid Chemistry – Hydrothermal fluids across Broken Spur, Rainbow, Lucky Strike (Ewan), Menez Gwen, and Bubblylon showed pronounced spatial and compositional variability. At **Broken Spur**, focused high-temperature vents (up to 368 °C, pH 3.9–4.9) contained elevated sulfide (2.7–4.8 mmol/L), Fe^{2+} (to 25 ppm), and high H_2/CH_4 ratios (3–5). Diffuse flows near mussel beds had <10 $\mu\text{mol/L}$ sulfide. At **Ewan**, low-temperature diffuse fluids (16–26 °C, pH 6.3–7.7) were reducing (Eh –30 to –270 mV) with moderate sulfide (37–278 $\mu\text{mol/L}$) and near-unity H_2/CH_4 ratios. The ultramafic **Rainbow** field exhibited the highest H_2 and CH_4 concentrations and extreme variability: main-vent fluids reached millimolar H_2 , CH_4 , and $H_2/CH_4 \approx 9$, while diffuse “Rainbow Pits” flows showed inverse patterns— CH_4 up to millimolar but H_2 only micromolar ($H_2/CH_4 \approx 0.0007$). Diffuse vents (10–96 °C) had sulfide 2–552 $\mu\text{mol/L}$, pH 6.2–7.3; focused vents (to 376 °C) reached 900 ppm Fe^{2+} , 1449 $\mu\text{mol/L}$ sulfide, and brine-like salinities. At **Menez Gwen** and **Bubblylon**, sulfide concentrations were also highly variable. Menez Gwen’s “White Flames” fluids (295 °C, pH 3.9–6.1) had up to 4.99 mmol/L sulfide, while Bubblylon’s reached 1.39 mmol/L. Diffuse flows showed several hundred $\mu\text{mol/L}$ sulfide and generally low H_2/CH_4 ratios (<1).

Molecular Ecology – Seventy-four ROV samples (fluids, seawater, solids) and forty-nine CTD samples were processed for microscopy, metagenomics, and diversity studies. Preliminary onboard sequencing from sulfur-oxidizing bacterial enrichments was completed for two key samples; further analysis will occur ashore.

Symbiosis Studies – Nanopore sequencing of *Bathymodiolus* from Broken Spur produced the most complete SOX-symbiont genome yet (3.1 Mbp, 17 contigs), suggesting low intraspecific diversity. Single-bacteriocyte isolations from Rainbow and Menez Gwen successfully preserved cell integrity for future metagenomic analysis. Ex-situ experiments showed potential symbiont release from dying gill tissue and feces, implying multiple colonization pathways. In-situ pumps collected free-living SUP05 and symbiont DNA from plumes, while “metabolite catcher” resins were deployed at Broken Spur and Menez Gwen to trap mussel-derived exometabolites for LC-MS/MS analysis.

Scientific Output

Data

Bach W, Schumacher M (2024): Multibeam bathymetry raw data (Kongsberg EM 122 entire dataset) of RV METEOR during cruise M190 [dataset]. PANGAEA: <https://doi.org/10.1594/PANGAEA.965783>

Bach W, Schumacher M (2024): Water column raw data (Kongsberg EM 122 entire dataset) of RV METEOR during cruise M190 [dataset]. PANGAEA: <https://doi.org/10.1594/PANGAEA.965784>

Kopte R, Bach W (2023): Shipboard ADCP current measurements (75 kHz) during RV METEOR cruise M190 [dataset]. PANGAEA: <https://doi.org/10.1594/PANGAEA.963746>

Cruise Report

M190: https://doi.org/10.48433/cr_m190

Submarine volcanism in the western Sicilian Channel

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

J. Geldmacher, C. Timm, K. Hoernle

Monterey Bay Aquarium Research Institute | Monterey, CA, USA

A. Micallef

University of Birmingham | Birmingham, UK

S. Watt

Introduction and geological background

Continental rifting gives rise to thinned lithosphere through extensional tectonics and is often associated with volcanism. The origin of this volcanism remains poorly understood relative to other volcano-tectonic settings on Earth and particular when covered by seawater as in the Sicilian Channel. This Channel is a shallow water platform (mainly <400 m in depth) in the central Mediterranean Sea, located between the southern coast of Sicily, eastern coast of Tunisia and the Malta Escarpment (Figure 1). It forms part of the northern African continental plate, thinned by extension since the late Miocene (Civile et al., 2008). The area is dominated by two large tectonic domains: 1) the Sicilian Channel Rift Zone consisting of the three NW-orientated Pantelleria, Linosa and Malta grabens and 2) the NNE-oriented Capo Grabitola Sciacca Fault Zone (CGSFZ), a lithospheric strike-slip fault zone, bounded by the Capo Granitola Fault system to the west and the Sciacca Fault system to the east (Figure 1).

The Sicilian Channel has been interpreted as a passive rift setting with pronounced crustal extension and a variety of volcanic landforms closely associated with extensional faults (Civile et al., 2010). The magmatism includes the volcanic islands of Pantelleria and Linosa, several submarine volcanic edifices (e. g., Graham, Terribile, Adventure, Nameless Banks), and buried dykes and sills (Civile et al., 2018) (Figure 1). Although some magmatic products date to 9.5 Ma (Nameless Bank, Beccaluva et al., 1981), the other four volcanoes that have been dated so far have

a Pliocene/Pleistocene to recent age (Calanchi et al., 1989; Rotolo et al., 2006). Submarine eruptions have been reported up to historical times.

Cruise M191 aimed to study how the volcanism of the Sicilian Channel has developed in conjunction with tectonic structures. Therefore, the seafloor was extensively mapped (with multibeam echo sounder, sediment echo sounder, and towed magnetometer) and potential volcanic structures were sampled (by chain bag dredges).

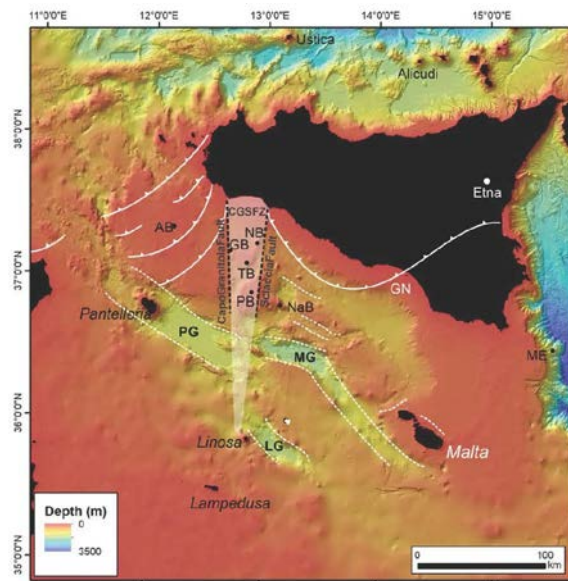


Figure 1: Bathymetric map of the Sicilian Channel with main structural and geo-morphic features labelled. PG: Pantelleria Graben; MG: Malta Graben; LG: Linosa Graben; GN: Gela Nappe; AB: Adventure Bank; GB: Graham Bank; TB: Terrible Bank; NB: Nerita Bank; NaB: Nameless Bank; PB: Pinne Bank; SMTF: Sicilian-Maghrebian Thrust Front; ME: Malta Escarpment; CGSFZ: Capo-Granitola-Sciaccia Fault Zone. Modified from Geldmacher et al. 2023.

Results and discussion

Seafloor Bathymetry and Magnetics

In total, 18 dedicated multibeam/magnetometer surveys, covering a total length of 2886 km, were conducted to record high-resolution bathymetric data, backscatter, water column profile data and the total magnetic field intensity (Figure 2). At Graham Bank (Figure 1) a previously unknown site of hydrothermal venting was observed in the midwater multibeam data. A further active flare was observed on NW Terrible Bank.

The collected magnetic field data, coupled with the high-resolution bathymetry often demonstrated an absence of shallow igneous material at sites that have previously been interpreted as volcanic, e. g., at two morphological seamounts around Linosa. In summary, the distribution of magmatism in Sicilian Channel is not only restricted to fewer sites than has previously been proposed, but reveals a spatial pattern that can be related to the dominant tectonic structures of the region (Micallef et al., 2024) (Figure 3).

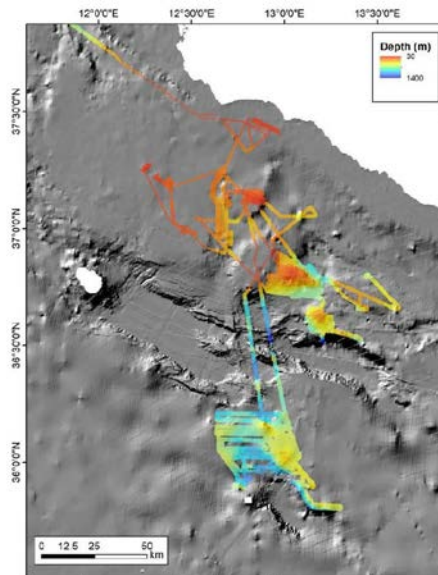


Figure 2: Coverage of multibeam echosounder bathymetry and PARASOUND acquired during M191 (taken from Geldmacher et al. 2023).

Volcanology/Igneous Geochemistry

Of the 68 dredge stations, only 11 returned empty or contained just unconsolidated mud. All others delivered carbonates, consolidated limestone and, at 24 dredge stations, igneous rocks. Three previously unknown volcanic outcrops were discovered and partly sampled. Going from south to north the findings are summarized in the following (see Figure 3 for location of specific sites).

Quaternary rift volcanism in the southern working area of the Pantelleria–Linosa grabens is concentrated at four main sites: Linosa, Pantelleria, Linosa III, and Pantelleria SE – closely aligned with the structural graben boundaries. These area features cones and mounded edifices stretching over 10 km with a 120° volcanic alignment.

North of the grabens, volcanic structures parallel the younger polygenetic systems to the south. Nameless Bank and the Adventure Bank chain share comparable

scale and orientation. Their association with faulted sedimentary banks suggests magmatism linked to crustal thinning and older feeder systems, predating present rifts (Micallè et al., 2024).

Subsurface igneous complexes in the northern Sicilian Channel (Pinne Bank, SE Pinne Bank, Cimotote) align with Nameless and Adventure Bank but lack volcanic features on the surface. Our geophysical data reveal the presence of intrusive bodies or buried volcanic masses, indicating a widespread and variably older magmatism in this sector. Likewise, Terrible Bank exhibits scattered magnetic anomalies over 10 km without clear seafloor morphology or alignment, consistent with eroded, polygenetic volcanism of considerable age.

The youngest volcanism is represented by monogenetic cones of the Graham Bank volcanic field (Holocene) and the northern CGSFZ (late Pleistocene–Holocene). Unlike the long-lived edifices to the south, these are small (<1 km), low-volume cones from shallow mafic eruptions. The field includes the shallow Ferdinandeia seamount, which temporarily formed an island during its eruption 1831. To test if this eruption was responsible for increased sulfur input and a global cooling event (Garrison et al., 2021), glass samples from this seamount were analyzed for volatiles and selected major elements (Hutchison et al., 2025).

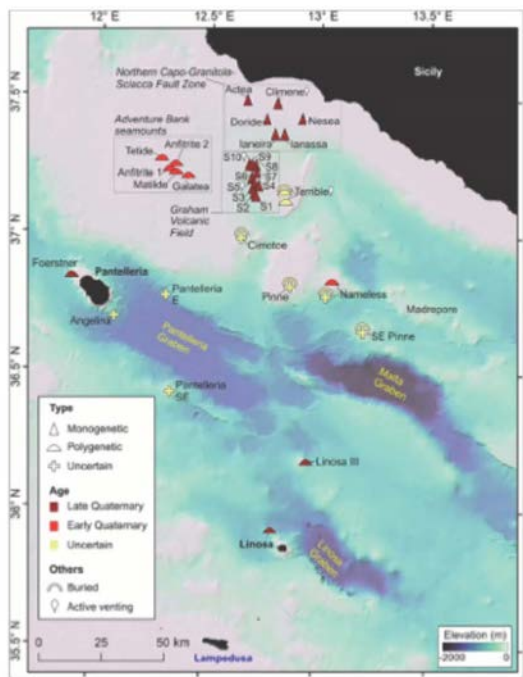


Figure 3: Revised map of the distribution of submarine volcanism across the western Sicilian Channel based on the preliminary result of Exp. M191 (taken from Micallè et al., 2024).

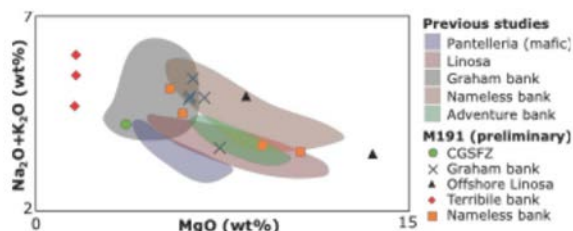


Figure 4: Preliminary whole rock MgO versus alkali concentration data obtained by XRF at the University of Edinburgh (S. Watt, A. Hodgetts, A. Micallef, E. Lawrence-Scholefield personal com., Sept. 2025). Colored reference fields from the literature.

Biogenic Carbonates

The recovered biological carbonate material included rhodolith-forming coralline algae but also red corals and fragments of solitary corals, serpulids, bryozoans, and encrusting foraminifera. Macro- and microscale analyses were integrated with water profile data to evaluate the origin and factors controlling the development of these carbonate bioconstructions as a function of water depths (Kiani Harchegani et al., in prep.). In comparison with other Mediterranean mesophotic systems, where heterotrophs are the main producers, the sampled shallow Terrible and Nameless Banks support coralline algae-dominated assemblages (rhodoliths) due to lower sediment input and higher water clarity.

Nannoplankton

In total, 82 surface water samples for nannoplankton research were taken along the entire ships track. During M191 the Mediterranean Sea experienced a severe heat wave reflected in increased surface water temperatures with values exceeding the average temperatures for the month of July by 4–6°C (Behr et al., 2025). The systematically conducted sampling of surface water plankton during the transect from Algeiras to Piraeus is currently used (a. o.) to investigate the response of calcifying phytoplankton to marine heatwaves as analogue to the expected increased sea surface temperatures due to global warming. Preliminary results indicate that certain calcifying plankton seem to switch from a diploid to a haploid life-stage as defense strategy during such extreme temperatures (Archontikis in prep.).

Acknowledgments

We would like to thank Master Derk Apetz and his skillful crew for their great support during M191 and we acknowledge funding by the German Research Association (DFG), LithoMar (International Lithosphere Program), and GEOMAR Helmholtz Centre for Ocean Research, Kiel. We are very grateful to Briese Research and the LDF for obtaining detailed data on the distribution of submarine cables in the working area, without which dredging at most positions could not have been carried out.

References

Behr L, Xoplaki E, Luther N, Josey SA & Luterbacher J, Atmospheric patterns drive merine heatwaves in the North Atlantic and Mediterranean Sea during summer 2023, *Environmental Research Letters* 2025, 20 (10), doi: 10.1088/1748-9326/ae0055.

Calanchi N, Colantoni P, Rossi PL, Saitta M & Serri G, The Strait of Sicily continental rift systems: Physiography and petrochemistry of the submarine volcanic centres, *Marine Geology* 1989, 87, 55–83.

Civile D, Lodolo E, Tortorici L, Lanzafame G & Brancolini G, Relationships between magmatism and tectonics in a continental rift: The Pantelleria Island region (Sicily Channel, Italy), *Marine Geology* 2008, 251, 32–46.

Civile D, Lodolo E, Accettella D, Geletti R, Ben-Avraham Z, Deponte M, Facchin L, Ramella R & Romeo R, The Pantelleria graben (Sicily Channel, Central Mediterranean): an example of intraplate 'passive' rift, *Tectonophysics* 2010, 490, 173–183.

Civile D, Lodolo E, Accaino F, Geletti R, Schiattarella M, Giustiniani M, et al., Capo Granitola-Sciacca Fault Zone (Sicilian Channel, Central Mediterranean): Structure vs magmatism, *Marine and Petroleum Geology* 2018, 96, 627–644.

Geldmacher J, Micallef A, Archontikis O, Felgendreher M, Ferrante GM, Ford J, Grech Licari J, Hauff F, Hauff S, Hodgetts A, Lang J, Meredew K, Timm C, Portnyagin M & Watt S, Submarine Volcanism in the Western Sicilian Channel, Cruise No. M191 (GPF 21-1_036), 16.07.2023–05.08.2023, Algeciras (Spain) - Piraeus (Greece), METEOR-Berichte. Begutachtungspanel Forschungsschiffe, Bonn, 2023, pp. 1–113. https://doi.org/10.48433/cr_m191.

Garrison G, Kilburn C, Smart D & Edwards S, The blue suns of 1831: Was the eruption of Ferdinandea, near Sicily, one of the largest volcanic climate forcing events of the nineteenth century?, *Clim. Past* 2021, 17, 2607–2632.

Hutchison W, Sugden P, Burke A, Abbott P, Ponomareva VV, Dirksen O, Portnyagin MV, MacInnes B, Bourgeois J, Fitzhugh B, Verkerk M, Aubry TJ, Engwell SL, Svensson A, Chellman NJ, McConnell JR, Davies S, Sigl M & Plunkett G, The 1831 CE mystery eruption identified as Zavaritskii cadera, Simushir Island (Kurils), *Proceedings of the National Academy of Sciences of the United States of America* 2025, 122 (1), Art.Nr.: e2416699122, DOI 10.1073/pnas.2416699122.

Micallef A, Geldmacher J, Watt SFL, Ferrante GM, Ford J, Lodolo E, Civile D, Hodgetts AGE, Felgendreher M, Grech Licari J, Hauff F, Hauff S, Lang J, Meredew K, Portnyagin M, Timm C, Berndt C, Cavallaro D, Muccini F & Hoernle K, Submarine

volcanism in the Sicilian Channel revisited, *Marine Geology* 2024, 474,
doi: 10.1016/j.margeo.2024.107342.

Rotolo SG, Castorina F, Cellura D & Pompilio M, Petrology and geochemistry of submarine volcanism in the Sicily Channel Rift, *The Journal of Geology* 2006, 1414, 355–365.

Scientific Output

List of Publications

Micallef A, Geldmacher J, Watt SFL, Ferrante GM, Ford J, Lodolo E, Civile D, Hodgetts AGE, Felgendreher M, Grech Licari J, Hauff F, Hauff S, Lang J, Meredew K, Portnyagin M, Timm C, Berndt C, Cavallaro D, Muccini F & Hoernle K, Submarine volcanism in the Sicilian Channel revisited, *Marine Geology* 2024, 474,
doi: 10.1016/j.margeo.2024.107342.

Hutchison W, Sugden P, Burke A, Abbott P, Ponomareva VV, Dirksen O, Portnyagin, MV, MacInnes B, Bourgeois J, Fitzhugh B, Verkerk M, Aubry TJ, Engwell SL, Svensson A, Chellman NJ, McConnell JR, Davies S, Sigl M & Plunkett G, The 1831 CE mystery eruption identified as Zavaritskii cadera, Simushir Island (Kurils), *Proceedings of the National Academy of Sciences of the United States of America* 2025, 122 (1), Art.Nr.: e2416699122, DOI 10.1073/pnas.2416699122.

In preparation:

Kiani Harcheganie F, Coletti G, Micallef A, Timm C & Watt SFL, Bioconstruction and carbonate production in mesophotic to deep settings on the northern flank of the Sicilian Channel (Terrible and Nameless Banks, Central Mediterranean), in preparation for *Marine Geology*.

Archontikis OA, Herrle JO, Geldmacher J & the M191 Expedition Scientists, Response of calcifying phytoplankton communities to the July 2023 heatwaves along a Mediterranean Transect, in preparation for *Journal of Plankton Research*.

List of conference presentations

2025 | **Paleo-communities across the mesophotic to deep zones of the Terrible and Nameless Banks, The Sicily Channel, Central Mediterranean.** EGU General Assembly 2025, Vienna, Austria, <https://doi.org/10.5194/egusphere-egu25-6926>

2025 | **Submarine volcanism in the Sicilian Channel revisited.** La Geologica marina in Italia-Sesto convegno dei geologi marini italiani, Rome, Italy, <https://www.cnr.it/it/eventi/allegato/14236>

Data

Thermosalinograph:

<https://doi.org/10.1594/PANGAEA.966339>

Multi beam (EM122):

<https://doi.org/10.1594/PANGAEA.965764>

Muti beam water column (EM 122):

<https://doi.org/10.1594/PANGAEA.967289>

Multibeam (EM710):

<https://doi.org/10.1594/PANGAEA.965769>

Multibeam water column (EM 710):

<https://doi.org/10.1594/PANGAEA.965771>

Outreach/Media

Expedition blog:

<https://www.oceanblogs.org/expedition-m191-suave/>

Press release:

<https://www.geomar.de/en/news/article/suave-brings-new-discoveries-in-the-mediterranean-sea>

Newspaper article:

<https://www.theguardian.com/world/2023/aug/09/three-possibly-active-underwater-volcanoes-discovered-off-sicily>

Cruise Report

M191: https://doi.org/10.48433/cr_m191

M192/1 and M192/2

BRIDging hydrothermal sites along the HELlenic Arc off Milos from shallow to deep (BRIDGEHELL)

Authors

MARUM – Center for Marine Environmental Sciences, University of Bremen | Bremen, Germany

S.I. Bühring, C. dos Santos Ferreira, M. Elvert, J.M. Maak, W. Bach, E. Bazhenova, C. Kleint, E. Schefuß

Faculty of Geosciences, University of Bremen | Bremen, Germany

W. Bach, A. Bach, C. Röttgen, E. Anagnostou, P. Kumawat, M. Elvert, B. Winkelhues

Constructor University | Bremen, Germany

A. Koschinsky, E. Anagnostou, E.-M. Meckel, I. Pedre, E. Kurahashi, J. Liao

Institute for Chemistry and Biology of the Marine Environment (ICBM) – Carl von Ossietzky University of Oldenburg | Oldenburg, Germany

M. Seidel

GeoZentrum Nordbayern - Friedrich-Alexander-University Erlangen-Nürnberg | Erlangen, Germany

K. Haase, W. Lehmann, F. Hampel, M. Keith, J. Falkenberg

Department of Geology and Geoenvironment, National and Kapodistrian University of Athens | Athens, Greece

P. Nomikou, K. Bejelou, D. Lampridou, S.P. Kiliyas, A. Belka, E. Varotsou, S. Kothri, D. Papanikolaou

Introduction

The M192 expedition with RV *METEOR* (August 2023) investigated the hydrothermal systems around Milos Island (Aegean Sea, Greece) as part of a broader effort to understand the geological, geochemical, and microbiological processes that occur along a depth gradient from shallow photic zones to deeper aphotic environments of the Hellenic Volcanic Arc. The cruise was conceived as a spin-off of the DFG Emmy Noether Group “Hydrothermal Geomicrobiology” (PI



S.I. Bühring) and aimed to bridge the traditional separation between shallow and deep-sea hydrothermal vents by studying them as a continuum. The Aegean Sea provides a unique natural laboratory, hosting both shallow coastal systems and deeper, subduction-related vent fields, thus enabling investigation of how venting, microbial diversity, and mineralization processes evolve with depth and distance from land (Dando et al. 2000; Nomikou et al. 2013; Bühring & Sievert 2017; Puzenat et al. 2021).

The scientific objectives of the expedition were threefold: (1) to map and locate hydrothermal vent sites using the vessel's EM710 multibeam system and the AUV MARUM-SEAL 5000, (2) to sample hydrothermal fluids, plumes, sediments, and microbial mats along a depth transect using a CTD rosette water sampler and the ROV MARUM-SQUID, and (3) to deploy in situ experiments to determine how the balance of autotrophy versus heterotrophy in microbial communities varies with depth. While objectives (1) and (2) were successfully achieved, objective (3) could not be carried out because the chamber lander systems originally intended for the autotrophy/heterotrophy experiments had been lost during an earlier expedition and were therefore not available for use.

Seafloor bathymetry and mapping of hydrothermal vent fields

The expedition nonetheless yielded a rich multidisciplinary dataset. Hydroacoustic surveys with the EM710 revealed extensive bubble plumes, while three AUV dives produced high-resolution maps of vent fields. A total of 26 CTD stations sampled water column anomalies indicative of hydrothermal input, enabling subsequent analyses of tracers, trace metals, and microbial interactions. In situ pumps were deployed at two stations to collect microbial biomass and biomarkers, with a focus on quantifying the integration of "old" hydrothermal carbon into modern microbial food webs. Sediments were recovered with grabs and a multicorer to assess porewater geochemistry, microbial diversity, and mineralogical transformations. Eight dives with the ROV MARUM-SQUID provided targeted samples of fluids, sediments, rocks, and microbial mats, as well as detailed imagery of seafloor habitats. Beyond the primary study area, surveys of unexplored seafloor around Milos were conducted to search for additional hydrothermal activity along volcanic edifices.

The first scientific outcomes of M192 are now emerging. A manuscript by Nomikou et al. (accepted) reports the discovery of this previously undocumented,

intermediate-depth hydrothermal vent field (30–230 m) on the shelf of Milos. Three vent areas – Aghia Kiriaki, Paleochori-Thiorychia, and Vani – were identified, structurally controlled by ENE–WSW and NW–SE trending faults (Figure 1). The venting shows a bi- to trimodal depth distribution, clustering around ~130 m, ~180 m, and ~210 m water depth. Shallower areas are dominated by sandy flats with gas discharge and microbial mats, while deeper sites host vigorous chimney edifices with fluid temperatures exceeding 180 °C. The clustering of vent depths broadly coincides with paleo-shorelines of the Last Glacial Maximum, suggesting that sea-level fluctuations and tectonic structures jointly controlled the preservation and distribution of venting on the continental shelf.

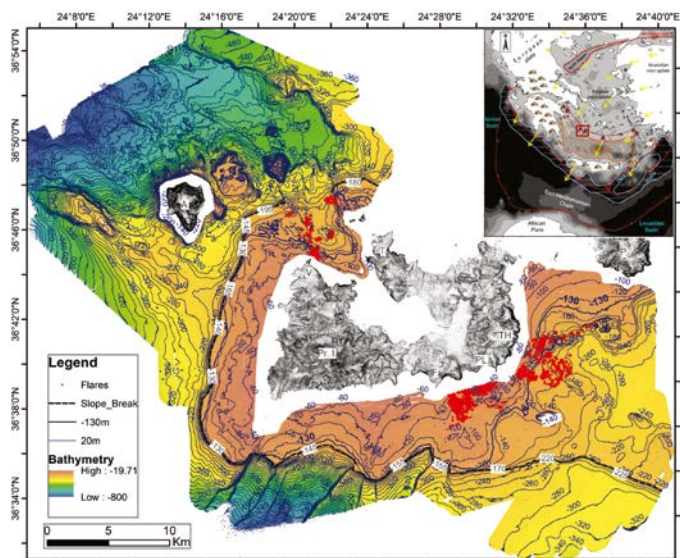


Figure 1: Bathymetric map of the studied area around Milos Island with 20 m contours. The 130 m depth contour is shown in dark blue, and the shelf-break as a thick black dashed line at varying depths. The detected flares interpreted as sites of active gas/hydrothermal venting are shown as red circles. Onshore topography is shown with shaded relief, and the very shallow coastal zone (<40 m depth) is left white. Inset map: The geotectonic frame of the Aegean Volcanic Arc (AVA) with the position of the Milos volcanic group (red rectangle) developed at the back-arc area of the Hellenic arc behind the Hellenic trenches, the Peloponnese-Crete-Dodekanese island arc and the Cretan Back-Arc Basin (CBAB) (Nomikou et al. accepted).

Fluid flow shapes microbial communities and mineralogy

A second study by Maak et al. (under review) highlights how contrasting fluid flow regimes strongly influence microbial ecology and mineral formation at the Milos vent field. Diffusive flow conditions, characterized by acidic and sulfate-rich fluids, foster sulfate-reducing microbial communities and lead to kaolinization and pyrite precipitation. In contrast, focused high-temperature venting delivers carbon-rich fluids that sustain sulfide-oxidizing chemoautotrophs, producing elemental sulfur

deposits. These findings demonstrate a direct coupling between fluid chemistry, microbial metabolism, and mineralogy, emphasizing the role of hydrothermal flow dynamics in shaping benthic ecosystems. Lipid biomarker analysis of hydrothermal sediments and chimneys collected during the M192 cruise, revealed distinct microbial adaptation strategies, with chimneys enriched in long-chain diacyl glycerol ethers (DAGEs) and methylated isoprenoid glycerol monoalkyl glycerol tetraethers (iGMGTs), and sediments dominated by branched glycerol dialkyl glycerol tetraethers (brGDGTs) and novel branched and mixed glycerol trialkyl glycerol tetraethers (GTGTs), reflecting differences in microbial communities shaped by temperature and geochemical stressors (Maak et al., in prep.).

Another manuscript (Hampel et al., in prep), focuses on the epithermal-style mineralization discovered at the 180–210 m vent clusters. Sulfate- and sulfide-rich chimneys were characterized using a suite of analytical methods (optical microscopy, SEM-EDX, XRD, EPMA, LA-ICP-MS). The mineral assemblages include barite, stibnite, realgar, orpiment, pyrite, metacinnabar, and Ag-rich sulfosalts (Figure 2). Geochemical analyses reveal enrichments in As, Ag, Hg, Sb, and Tl, indicating that epithermal mineralization processes known from onshore Milos extend into the submarine environment. Ongoing work integrates whole-rock geochemistry with stable sulfur and radiogenic strontium–neodymium isotopes to elucidate the depth-dependent transition from shallow to deeper hydrothermal venting and its implications for ore-forming processes in subduction-related volcanic arcs.

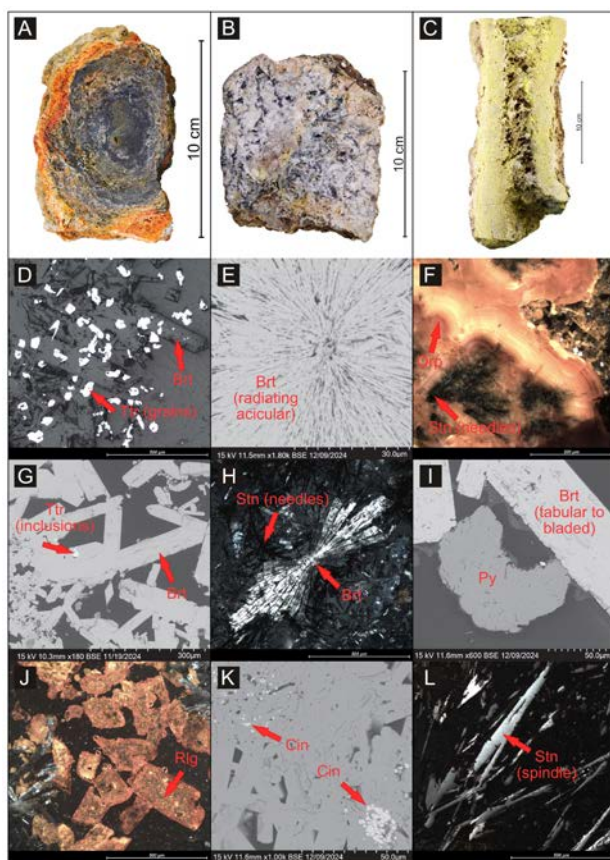


Figure 2: Photographs (A-C), micrographs (D, F, H, J, L), and electron micrographs (E, G, I, K) of the sulfides and sulfates representative for the shallow-marine hydrothermal mineralization around Milos Island, Greece. (A) As-/Sb-sulfide-rich sample type, (B) barite-dominated sample type, (C) native-sulfur-dominated sample type. (D) Tabular to bladed barite associated with various Ag-rich polyminerals accumulates of Sb-sulfosalts, (E) radiating acicular barite, (F) spherical orpiment with intergrown needles of stibnite, (G) the aforementioned sulfosalts as inclusions in barite, (H) stibnite needles surrounding and intergrown with barite, (I) pyrite grains associated with tabular barite, (J) blocky to rhombohedral realgar enclosing tabular barite, (K) granular metacinnabar associated with As-sulfides and barite, (L) spindle-like to bladed stibnite. Abbreviations: Brt: barite, Orp: orpiment, Py: pyrite, Ttr: tetrahedrite, Cin: cinnabar, Rlg: realgar, Stn: stibnite.

Dissolved organic matter (DOM) transformations

At the Paleochori-Thiorychia vent sites in 50 to 200 depth, solid-phase extracted DOM (SPE-DOM) was enriched compared to hydrothermally less influenced sites, while bulk DOC concentrations remained unchanged. Bulk DOC reflects total concentrations, whereas SPE-DOM captures molecular fractions such as hydrophobic, likely more recalcitrant DOM. Our preliminary results suggest selective hydrothermal alteration of marine DOM, modifying the molecular DOM composition without an apparent change in total DOC concentrations. With

our ongoing ultrahigh-resolution mass spectrometry analyses we aim to clarify whether hydrothermal alteration at the vent sites, including sulfurization of DOM under sulfidic conditions, or sedimentary inputs drive these changes. Radiocarbon dating will further help to distinguish recently mobilized, bioavailable components from older, recalcitrant DOM fractions, thereby helping to constrain the role of hydrothermal systems in marine DOM cycling.

Conclusions

Overall, the M192 cruise provided an unprecedented multidisciplinary dataset spanning geology, geochemistry, microbiology, and mineralogy of hydrothermal systems along a depth transect in the Aegean Sea. By integrating shallow and intermediate-depth venting environments into a single framework, this work advances our understanding of hydrothermal systems as dynamic continua, shaped by the interplay of tectonics, sea-level change, fluid chemistry, and microbial activity. The results from M192 not only shed light on the processes governing present-day seafloor ecosystems but also have implications for paleoenvironmental reconstructions, the formation of mineral deposits, and the assessment of chemosynthetic habitability in submarine volcanic settings.

References

- Dando PR, Aliani S, Arab H, Bianchi CN, Brehmer M, Cocito S, Fowler SW, Gundersen J, Hooper LE, Kolbl R, Kuever J, Linke P, Makropoulos KC, Meloni R, Miquel JC, Morri C, Muller S, Robinson C, Schlesner H, Sievert S, Stohr R, Stuben D, Thomm M, Varnavas SP & Ziebis W, Hydrothermal studies in the Aegean Sea, *Physics and Chemistry of the Earth Part B-Hydrology Oceans and Atmosphere* 2000, 25(1), 1–8.
- Nomikou P, Papanikolaou D, Alexandri M, Sakellariou D & Rousakis G, Submarine volcanoes along the Aegean volcanic arc, *Tectonophysics* 2013, 597–598, 123–146.
- Bühning SI & Sievert SM, The shallow submarine hot vent system off Milos (Greece) – a natural laboratory to study hydrothermal geomicrobiology In, Kallmeyer J (ed), *Life at Vents and Seeps (Life in Extreme Environments)* 2017, De Gruyter.
- Puzenat V, Escartín J, Martelat J-E, Barreyre T, Le Moine Bauer S, Nomikou P, Gracias N, Allemand P, Antoniou V, Coskun O, Garcia R, Grandjean P, Jørgensen SL, Magí L, Mandalakis M, Orsi W, Polymenakou P, Schouw A, Vallicrosa G & Vlasopoulos O, Shallow-water hydrothermalism at Milos (Greece): Nature, distribution, heat fluxes and impact on ecosystems, *Marine Geology* 2021, 438, 106521.

Nomikou P, Bejelou K, Koschinsky A, Dos Santos Ferreira C, Papanikolaou D, Lampridou D, Kilias SP, Anagnostou E, Elvert M, Röttgen C, Maak JM, Bach A, Bach W, Belka A, Bazhenova E, Haase K, Kleint C, Varotsou E, Kumawat P, Kurahashi E, Liao J, Meckel E-M, Pedre I, Lehmann W, Schefuss E, Seidel M, Kothri S & Bühring SI, (accepted), Structural Control and Depth Clustering of Extensive Hydrothermal Venting on the Shelf of Milos Island, Scientific Reports.

Maak JM, Röttgen C, Winkelhues B, Anagnostou E, Bach W, Bühring SI, Koschinsky A, Liao J, Vogt C, Schefuß E & Elvert M, (under review), Diffusive and advective fluid flow shapes chemoautotrophic bacterial communities and sulfur mineralogy in hydrothermal sediments off Milos, Environmental Microbiology, <https://doi.org/10.1101/2025.09.02.673406>.

Scientific Output

List of Publications

Röttgen C, Impact of environmental conditions on lipid composition in hydrothermally influenced sediments off Milos, Greece, MSc thesis, University of Bremen 2025.

Winkelhues B, Mineral composition of sediments and rocks in the submarine hydrothermal system off Milos (Greece): Biological or geological control? BSc thesis, University of Bremen 2025.

Belka A, Submarine Volcanic Morphology of Antimilos volcano, Greece, MSc thesis, National & Kapodistrian University of Athens 2024.

Belka A, Nomikou P, Bühring SI, Bejelou K, Lampridou D, Kothri S, Varotsou E, Bach A & Papanikolaou D, (under review), The Antimilos Volcanic Group with emphasis on its submarine volcanoes, Aegean Sea, Geological Society of London Special Publication.

Maak JM, Röttgen C, Winkelhues B, Anagnostou E, Bach W, Bühring SI, Koschinsky A, Liao J, Vogt C, Schefuß E & Elvert M, (under review), Diffusive and advective fluid flow shapes chemoautotrophic bacterial communities and sulfur mineralogy in hydrothermal sediments off Milos, Environmental Microbiology, <https://doi.org/10.1101/2025.09.02.673406>.

Nomikou P, Bejelou K, Koschinsky A, Dos Santos Ferreira C, Papanikolaou D, Lampridou D, Kilias SP, Anagnostou E, Elvert M, Röttgen C, Maak JM, Bach A, Bach W, Belka A, Bazhenova E, Haase K, Kleint C, Varotsou E, Kumawat P, Kurahashi E, Liao J, Meckel E-M, Pedre I, Lehmann W, Schefuss E, Seidel M, Kothri S & Bühring SI, (under review), Extensive Intermediate-Depth Hydrothermal Venting off Milos Island: Structural Alignment and Depth Clustering, Scientific Reports.

Maak JM, Röttgen C, Bühring SI, Schefuß E & Elvert M, (in preparation), Toxic niches in hydrothermal chimneys captured by stress-adapted lipids.

Hampel F, Falkenberg J, Keith M, Bühring SI, Bach W, Regelous M, Strauß H & Haase K, (in preparation), Active shallow-marine venting and associated epithermal-style mineralization around Milos Island, Greece.

List of conference presentations

2025 | **Geochemical Control on Microbial Lipid Distributions in Hydrothermal Sediments Off Milos (GREECE)**, International Meeting of Organic Geochemistry (IMOG), Porto, Portugal

2025 | **Lipid biomarkers and their stable carbon isotopes in hydrothermal sediments as life markers of chemoautotrophy under extreme conditions**, Goldschmidt Conference, Prague, Czech Republic

2025 | **Geochemical and mineralogical drivers of microbial life in hydrothermal systems** (oral), Goldschmidt Conference, Prague, Czech Republic

2025 | **A Transitional Hydrothermal Vent Field on the Milos Shelf (Aegean Sea, Greece): Bimodal Distribution Influenced by Tectonics and Sea-Level Change**, Goldschmidt Conference, Prague, Czech Republic

2025 | **First geochemical insights into newly discovered shallow hydrothermal vent fields near Milos, Greece**, Goldschmidt Conference, Prague, Czech Republic

2025 | **Epithermal-style mineralisation at active shallow-submarine vents, Milos Island, Greece**, Goldschmidt Conference, Prague, Czech Republic

2025 | **Oceanographic survey M192 off Milos reveals tectonic controls on hydrothermal vent distribution in a complex volcanic-tectonic system of the South Aegean**, 17th International Congress of the Geological Society of Greece, Lesbos island, Greece

2025 | **Morphotectonic analysis of Antimilos volcanic Group**, 17th International Congress of the Geological Society of Greece, Lesvos island, Greece

2024 | **Discovery of a unique submarine hydrothermal system between shallow photic and deep dark sites around the Greek island of Milos (Aegean Sea, Greece)**, EGU General Assembly, Vienna, Austria

2024 | **Submarine volcanic structures from high resolution swath data around Antimilos Aegean Sea, Greece**, 2nd International Conference on Seafloor Landforms, Processes and Evolution, Lipari, Italy

2024 | **New insights into the morphology, extent and distribution of hydrothermal vents in the unique shallow-submarine volcanic seabed around Milos, Aegean Sea, Greece**, 2nd International Conference on Seafloor Landforms, Processes and Evolution, Lipari, Italy

Data

Master tracks in different resolutions of METEOR cruise M192/1, Piraeus – Piraeus, 2023-08-08–2023-08-18 [dataset], MARUM – Center for Marine Environmental Sciences, University Bremen by Bühring, SI (2023), PANGAEA:
<https://doi.org/10.1594/PANGAEA.963981>

Master tracks in different resolutions of METEOR cruise M192/2, Piraeus – Limassol, 2023-08-20–2023-09-05 [dataset] by Bühring, SI (2023), MARUM – Center for Marine Environmental Sciences, University Bremen, PANGAEA:
<https://doi.org/10.1594/PANGAEA.964215>

Master track of METEOR cruise M192/1 in 1 sec resolution (zipped, 36.2 MB) [dataset] by Bühring, SI (2023), MARUM – Center for Marine Environmental Sciences, University Bremen, PANGAEA:
<https://doi.org/10.1594/PANGAEA.963980>

Master track of METEOR cruise M192/2 in 1 sec resolution (zipped, 58.0 MB) [dataset] by Bühring, SI (2023), MARUM – Center for Marine Environmental Sciences, University Bremen, PANGAEA:
<https://doi.org/10.1594/PANGAEA.964216>

Continuous thermosalinograph oceanography along RV METEOR cruise track M192/1 [dataset] by Schlundt, M, Bühring, SI (2024), PANGAEA:
<https://doi.org/10.1594/PANGAEA.972624>

Continuous thermosalinograph oceanography along RV METEOR cruise track M192/2 [dataset] by Schlundt, M, Bühring, SI (2024), PANGAEA:
<https://doi.org/10.1594/PANGAEA.972625>

Shipboard ADCP current measurements (38 kHz) during RV METEOR cruise M192/2 [dataset] by Kopte, R, Bühring, SI (2024), PANGAEA:
<https://doi.org/10.1594/PANGAEA.974227>

ADCP current measurements (75 kHz) during RV METEOR cruise M192/2 [dataset] by Kopte, R, Bühring, SI (2024): Shipboard PANGAEA:
<https://doi.org/10.1594/PANGAEA.974226>

Water column raw data (Kongsberg EM710 entire dataset) of RV METEOR during cruise M192/2 [dataset] by Bühring, SI, Nomikou, P, Bach, A (2024), PANGAEA:
<https://doi.org/10.1594/PANGAEA.968509>

Multibeam bathymetry raw data (Kongsberg EM710 entire dataset) of RV METEOR during cruise M192/2 [dataset] by Bühring, SI, Nomikou, P, Bach, A (2024), PANGAEA, <https://doi.org/10.1594/PANGAEA.968508>

Water column raw data (Kongsberg EM710 entire dataset) of RV METEOR during cruise M192/1 [dataset] by Bühring, SI, Nomikou, P, Lampridou, D, Bejelou, K, Kothri, S, Varotsou, E, Belka, A, Bazhenova, E, dos Santos Ferreira, C (2024), PANGAEA: <https://doi.org/10.1594/PANGAEA.968507>

Orthomosaic, Digital Elevation Model (DEM) and textured 3D Model of the White Seal-Hound hydrothermal vent in the Aegean Sea, from ROV SQUID dive videos, RV METEOR Expedition M192/2 [dataset in review] by Marcon, Y, Bühring, SI, PANGAEA: <https://doi.pangaea.de/10.1594/PANGAEA.974816>

Fatty acid concentrations, compound-specific carbon stable isotopes, mineralogy, and porewater data of sediments from the hydrothermal vent system off Milos, Greece [dataset bundled publication] by Maak, JM, Röttgen, C, Winkelhues, B, Anagnostou, E, Bach, W, Bühring, SI, Koschinsky, A, Liao, J, Vogt, C, Schefuß, E, Elvert, M, PANGAEA, <https://doi.pangaea.de/10.1594/PANGAEA.984736> (dataset in review)

XRD mineralogical abundances in sediments off Milos, Greece [dataset] by Maak, JM, Röttgen, C, Winkelhues, B, Anagnostou, E, Bach, W, Bühring, SI, Koschinsky, A, Liao, J, Vogt, C, Schefuß, E, Elvert, M, PANGAEA, <https://doi.pangaea.de/10.1594/PANGAEA.984720> (dataset in review)

Diverse porewater parameters measured in sediments off Milos, Greece [dataset] by Maak, JM, Röttgen, C, Winkelhues, B, Anagnostou, E, Bach, W, Bühring, SI, Koschinsky, A, Liao, J, Vogt, C, Schefuß, E, Elvert, M, PANGAEA, <https://doi.pangaea.de/10.1594/PANGAEA.984708> (dataset in review)

Total organic carbon and total sulfur in sediments off Milos, Greece [dataset] by Maak, JM, Röttgen, C, Winkelhues, B, Anagnostou, E, Bach, W, Bühring, SI, Koschinsky, A, Liao, J, Vogt, C, Schefuß, E, Elvert, M, PANGAEA, <https://doi.pangaea.de/10.1594/PANGAEA.984624> (dataset in review)

Mean compound-specific $\delta^{13}\text{C}$ values in sediments off Milos, Greece [dataset] by Maak, JM, Röttgen, C, Winkelhues, B, Anagnostou, E, Bach, W, Bühring, SI, Koschinsky, A, Liao, J, Vogt, C, Schefuß, E, Elvert, M, PANGAEA, <https://doi.pangaea.de/10.1594/PANGAEA.984735> (dataset in review)

Concentrations of fatty acids in sediments off Milos, Greece [dataset] by Maak, JM, Röttgen, C, Winkelhues, B, Anagnostou, E, Bach, W, Bühring, SI, Koschinsky, A, Liao, J, Vogt, C, Schefuß, E, Elvert, M, PANGAEA, <https://doi.pangaea.de/10.1594/PANGAEA.984726> (dataset in review)

Cruise Report

M192/1 & M192/2: https://doi.org/10.48433/cr_m192

M193

REPLENISH: Red Sea Paleoenvironmental Evolution under Monsoon fluctuations in the Pleistocene to Holocene

Authors

University of Hamburg, Institute of Geology | Hamburg, Germany
T. Lüdmann

Leibniz Centre for Tropical Marine Research (ZMT) | Bremen, Germany
H. Westphal

Introduction

Although the Red Sea is situated within the Saharo-Arabian desert belt – a key area for palaeoclimatic and palaeoanthropological research – its marine realm, including climate archives, has only been studied locally and sporadically. Therefore, cruise M193 aimed to investigate the present depositional environment under arid conditions, extending the study back to the Pleistocene period, when phases of humidity alternated with periods of aridity. The study area was located at the northern Saudi-Arabian margin in the vicinity of the Al Wajh carbonate platform (Figure 1) This region is characterized by a deep-sea fan fed by one of the largest onshore drainage systems on the Arabian Peninsula during Pleistocene pluvial phases. Reflection seismic measurements were conducted to investigate the evolution of the Late Pliocene to recent marginal sediment system under changing sea-level and climatic conditions, while gravity coring of isolated and connected sediment basins allows for high-resolution studies of Upper Pleistocene humidity-aridity phases. Mapping and sampling of the largely unstudied deep-water coral habitats via ROV, along with taxonomy studies, rounded up our survey.

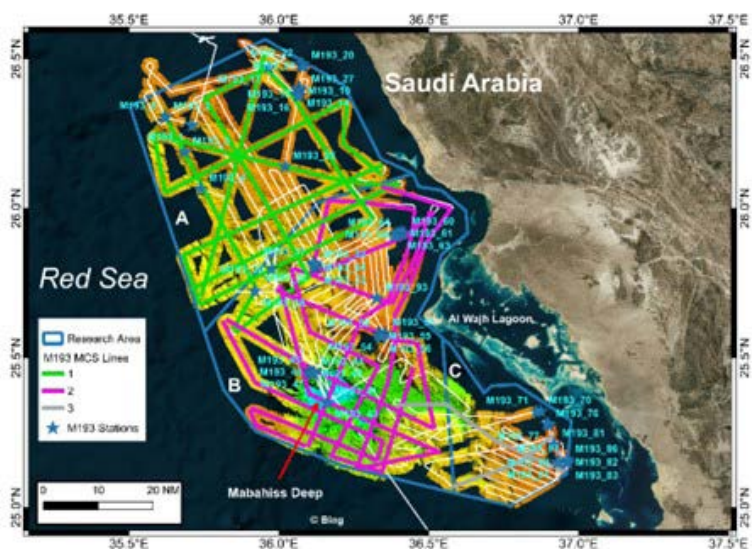


Figure 1: Overview of the M193 survey area.

Tectonic regime and depositional setting

Mobilized salt is the primary factor shaping the distinctive hilly topography of the present-day seafloor in the study area (Figure 1). The spatial distribution and morphology of the various subsurface salt structures provide important insights into the prevailing tectonic regime. Although the arrangement of these salt structures is complex, three distinct domains are identified. The first domain encompasses the Al Wajh carbonate platform (AWCP) and its adjacent slopes. The AWCP developed atop Pliocene siliciclastic sediments, which are likely underlain by landward-dipping half-grabens and mobilized salt (Baby et al., 2024). Under the load exerted by overlying sediment and carbonate buildups, the underlying salt likely migrated basinward following the pressure gradient (Smith & Santamarina, 2022), accumulating along the slopes and forming large salt anticlines. Salt flow is also thought to have contributed to the destabilization of the southern platform margin, where platform parts fractured and subsequently rafted atop the mobile salt layer (Petrovic et al., 2023). The second domain is located offshore, north of the AWCP. In this zone, elongated salt structures such as salt walls and associated minibasins trend nearly NNW–SSE, that is, parallel to the suggested rift axis. These features are interpreted to be related to basement-involved extension; above seaward dipping rift faults as described for this region. The third domain, located around the principal deformation zone, is likewise dominated by thick-skinned tectonics. Here, salt structures are primarily controlled by the prevailing stress field associated with the transtensional fault zone, involving the basement and entire sedimentary column. The Mabahiss Deep (Figure 1), is part of this zone and functions as a pull-apart basin.

ITCZ shifts and monsoon records in Red Sea Ocean basin

Sapropels represent a distinct indicator for monsoon run-off in the Mediterranean Sea, especially related to the African Monsoon. For the last 250 ka, around nine sapropels (S1 to S9) are documented for the E Mediterranean Sea (William et al., 2015; Grant et al., 2017). Their formation is closely linked to increased river discharge, which influenced the water circulation and resulted in a stratification of the water body. In addition, increased river-discharge is known to have strengthened marine productivity via enhanced nutrient input, contributing to sapropel formation (e. g. Krom et al., 1999). The increased river-discharge reflects the shift from relatively arid to more humid phases in N Africa that is controlled by the ITCZ. Similar to N Africa, the Red Sea region including the Arabian Peninsula (speleothem records) experienced humid (or pluvial) periods over at least the last 1.1 million years (e. g. Nicholson et al., 2020). As a consequence of the increased river discharge through reactivated large-scale onshore Wadi systems during these periods, Red Sea sediments were thought to host a similar number of sapropels. Moreover, the restricted oceanographic conditions of the Red Sea with high salinity and slow convection are expected to support sapropel formation. Nevertheless, so far only two sapropels (S1a and S1b) have been documented for the Red Sea basin that formed between 10–14 ka (e. g. Emmermann et al., 1999; Arz et al., 2003; Stein et al., 2007) as compared to S1 (5–10 ka) in the Mediterranean Sea (e. g. Grant et al., 2017). Moreover, several studies were performed on cores from the central Red Sea basin that have a high potential to suffer the influence and overprint through hydrothermal fluids (e. g. Laurila et al., 2015), which can be excluded for the herein presented study area. Planktic foraminiferal assemblages have been proposed as a proxy for monsoonal activity in the Red Sea to overcome the limitations of geochemical proxies in this extreme environment (Siccha et al. 2009). Long cores recovered during M193 yield a continuous record reaching to about 20 ka, and based on preliminary observations we expect to complement and extend the record of sapropels in the Red Sea.

Red Sea shallow-water, mesophotic and deep-water reef habitats

Ocean warming, acidification, and deoxygenation, among other co occurring factors, are shifting species ranges throughout the marine environment and across the entire depth gradient. Mesophotic and deep corals are understudied in their response to climate changes, particularly in the Red Sea, which has uniquely high temperatures and salinities in deep waters. Macrina et al. (accepted) on the basis of ROV footage from multiple cruises, including M193, assessed the diversity of octocorals in the mesophotic realm of the Red sea. On a similar data base, Nolan et al. (submitted) by predictive modelling estimated the area of suitable habitat for four mesophotic and deep-sea corals (*Acanthogorgia* spp.,

Stylaster tritoni, *Bathypathes thermophila* and *Madracis interjecta*) across the whole Red Sea under present conditions and under different scenarios of future environmental changes (years 2090–2100). We find variations in the responses of these corals, but three of the four are projected to lose significant amounts of their current habitats. In particular, the hydrocoral *S. tritoni* is likely to lose the largest proportion of its habitat, while the black coral *B. thermophila* may experience the least change. Deeper areas may become suitable for these corals, but colonisation will depend on their ability to disperse. We also assessed the potential biodiversity hotspots both now and, in the future, finding the northern Red Sea to be one ecologically important area. The M193 data thus contributes to important foundational data and knowledge for marine spatial planning in the region, in support of an effective and well-informed reserve design for long-term protected areas. Stühr et al. (2025) addressed the issue of erratic occurrences of shallow-water photosymbiotic benthic foraminifers in deep sea sediments recovered during M193. Large shallow-marine foraminifers were found in deep-sea carbonate sediments of the northern Red Sea as a minor but recurring component in otherwise pelagic and deep-marine benthic skeletal assemblages recovered from between 430 to 1,000 m water depth. Taxa included the symbiont-bearing *Sorites variabilis*, *S. orbiculus*, *Amphisorus hemprichii*, and *Amphistegina* spp., all dwelling in shallow-water environments, usually associated with seagrass and coral reef habitats. Exceptional preservation of such foraminifers along with, and still attached to, seagrass leaves and other macrophyte remains in a brine pool at ~630 m water depth. This supports the hypothesis of passive rafting by floating seagrass to offshore settings beyond the reach of gravitational off-platform transportation. Also, such long-distance dispersal mechanisms may likewise facilitate the rapid distribution into new habitats and thus play a crucial role in biogeographic patterns.

Plastic pollution in the Red Sea

As a side product of M193, we analysed all ROV footage recovered during the cruise with respect to the presence of plastic macrolitter (Castellan et al., 2025). The results showed that this type of pollution is very scarce in the Red Sea. The study serves as a baseline for assessing the effect of the development of tourist destinations and economic hubs in this area of the Red Sea.

References

Arz HW, Pätzold J & Müller PJ, Influence of Northern Hemisphere climate and global sea level rise on the restricted Red Sea marine environment during termination I, *Paleoceanography and Paleoclimatology* 2003, 18, 1053.

Baby G, Delaunay A, Rouby D, Ye J, Pensa T & Afifi MA, Sediment routing systems of the eastern Red Sea rifted margin, *Earth-Science Reviews* 2024, 249, 104679.

Emmermann P, Reijmer JJG & Andresen N, Sedimentation Rates of Late Quaternary Periplatform Sediments based on Aragonite/Calcite ratios: Sudanese Red Sea versus Pedro Bank (Caribbean), *GeoResearch Forum* 1999, 5, 67–86.

Grant KM, Grimm R, Mikolajewicz U, Marino G, Ziegler M & Rohling EJ, The timing of Mediterranean sapropel deposition relative to insolation, sea-level and African monsoon changes, *Quaternary Science Review* 2017, 140, 125–141.

Krom MD, Cliff RA, Eijssink LM, Herut B & Chester R, The characteristics of Saharan dusts and Nile particulate matter in surface sediments from the Levantine basin using Sr isotopes, *Marine Geology* 1999, 155, 319–330.

Laurila TE, Hannington M, Leybourne MD, Petersen S, Devey CW & Garbe-Schönberg D, New insights into the mineralogy of the Atlantis II Deep metalliferous sediments, Red Sea, *Geochem. Geophys. Geosyst.* 2015, 16, 4449–4478.

Nicholson SL, Pike AWG, Hosfield R, Roberts N, Sahy D, Woodhead J, Cheng H, Edwards RL, Affolter S, Leuenberger M, Burns SJ, Matter A & Fleitmann D, Pluvial periods in Southern Arabia over the last 1.1 million-years, *Quaternary Science Review* 2020, 229, 106112.

Petrovic, A, Lüdmann T, Saitz Y, Afifi AM, Betzler C & Vahrenkamp V, Fragmentation, rafting, and drowning of a carbonate platform margin, *Geology* 2023, 51, 242–246, <https://doi.org/10.1130/G50546.1>.

Siccha M, Trommer G, Schulz H, Hemleben C & Kucera M, Factors controlling the distribution of planktonic foraminifera in the Red Sea and implications for the development of transfer functions, *Marine Micropaleontology* 2009, 72, 146–156.

Smith JE & Santamarina JC, Red Se evaporites: Formation, creep and dissolution, *Earth-Science Reviews* 2022, 232, <https://doi.org/10.1016/j.earscirev.2022.104115>.

Stein M, Almogi-Labin A, Goldstein SL, Hemleben C & Starinsky A, Late Quaternary changes in desert dust inputs to the Red Sea and Gulf of Aden from $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in deep-sea cores, *EPSL* 2007, 261, 104–119.

Williams MAJ, Duller GAT, Williams FM, Woodward JC, Macklin MG, El Tom OAM, Munro RN, El Hajaz Y & Barrows TT, Causal links between Nile floods and eastern Mediterranean sapropel formation during the past 125 kyr confirmed by OSL and radiocarbon dating of Blue and White Nile sediments, *Quaternary Science Review* 2015, 130, 89–108.

Scientific Output

List of Publications

Lüdmann T, Westphal H, Petrovic A & Vahrenkamp V, Post-Miocene transtensional opening of the northern Red Sea, in preparation.

Nolan MKB, Assis J, Marchese F, Dunn N, Watts ME, Falkenberg P, Augustin N, Lüdmann T, van der Zwan FM, Westphal H, Qurban M, Pieribone V, Duarte CM & Benzoni F, Projected climate change impacts on deep sea corals of the Red Sea, Subm. to Global Change Biology.

Macrina L, Terraneo TI, McFadden CS, Chimienti G, Marchese F, Vimercati S, Vicario S, Reimer JD, Purkis SJ, Eweida AA, Pieribone V, Qurban M, Duarte CM, Rodrigue M, van der Zwan FM, Augustin N, Westphal H & Benzoni F, The hidden diversity of Red Sea Octocorals: a morpho-molecular assessment across bathymetric and latitudinal gradients, Accepted for publication in Sci Rep.

Castellan G, Marchese F, Lüdmann T, Taviani M & Westphal H, Marine macrolitter in the deep Red Sea offshore Al Wajh (Saudi Arabia): New evidence from benthic visual surveys. Regional Studies in Marine Sciences 2025, 89, 104357, doi: 10.1016/j.rsma.2025.104357.

Stuhr M, Westphal H, Marchese F, Mateu Vicens G, Giovenzana F, Lüdmann T, Vahrenkamp V & Taviani M, Seagrass-rafterd large benthic foraminifera disperse into the deep Red Sea. Scientific Reports 2025, 15:5724, doi:10.1038/s41598-025-90047-7.

List of conference presentations

2024 | **Red Sea anoxic brine pools act as taphonomic traps for organic remains**, IAS Meeting, Aberdeen, Scotland

2025 | **Sedimentological and Palaeoceanographic Signatures of a Newly Identified Late Pleistocene Sapropel in the Northern Red Sea**, IAS Meeting, Huelva, Spain

2025 | **Microbial stabilization of modern carbonates from the intertidal to the aphotic – a critical component of limestone lithification in the Red Sea**, SEPM Conference, Houston, USA

Data

Multibeam bathymetry (EM710):
<https://doi.org/10.1594/PANGAEA.968510>

Multibeam bathymetry (EM122):
<https://doi.org/10.1594/PANGAEA.968512>

Water column data (EM710):
<https://doi.org/10.1594/PANGAEA.968511>

Water column data (EM122):
<https://doi.org/10.1594/PANGAEA.968513>

Thermosalinograph:
<https://doi.org/10.1594/PANGAEA.971600>

Cruise Report

M193: https://doi.org/10.48433/cr_m193

M194

Activity, Distribution, and Biodiversity of Hydrothermal Vent Sites in the Red Sea, M194 HEXPLORES

Authors

OceanQuest Foundation | Thuwal, Saudi Arabia

N. Augustin

King Abdullah University of Science and Technology | Thuwal, Saudi Arabia

F. M. van der Zwan, F. Benzonì, A. S. Rosado

GEOMAR Helmholtz Centre for Ocean Research | Kiel, Germany

S. Petersen, S. G. Sander

British Antarctic Survey | Cambridge, United Kingdom

K. Linse

Introduction

The Red Sea Rift is a young (~13 Ma) ultra-slow spreading center (<16 mm/yr) characterized by a narrow axial trough partially filled by Miocene evaporites (Augustin et al., 2021). The basin's bottom water is exceptionally warm till almost 3000m depth (~21°C) and high in salinity (~41‰) due to restricted seawater exchange with open oceans, making it one of the harshest deep-sea environments we know. Geologically, the rift shows abundant volcanic activity, often flanked by or penetrating through thick salt sequences (Augustin et al., 2016; Preine et al., 2025), and it hosts unique (hot) brine pools and metalliferous sediments in several deeps (e. g., Schmidt et al., 2015). However, no active hydrothermal vents had been confirmed in the Red Sea for decades, leaving fundamental questions about this nascent ocean's hydrothermal systems. In 2022, the first active venting at Hatiba Mons volcano (23°N) was found and documented in large detail (van der Zwan et al., 2023). More than 40 diffuse, low-temperature vent sites have been identified, characterized by extensive Fe-oxide mounds and abundant microbial activity. However, no high-temperature vents or specialized fauna had been found. This discovery raised new questions: was Hatiba Mons unique, or one of many such systems along the rift?

The Meteor expedition M194 HEXPLORES (October 10–November 6, 2023) was designed to systematically explore the Red Sea Rift for active venting, addressing these key knowledge gaps. One objective was to test whether an ultra-slow ridge with high heat flow can host more and/or larger hydrothermal sites than predicted by global ridge trends. Another focus was to determine how evaporite deposits affect Red Sea fluid chemistry, e. g., salinity, metal content, and gas composition. Finally, the expedition aimed to document any vent-associated life, from microbial mats to macrofauna, to determine whether the Red Sea vents harbor unique biota or only sparse colonizers, given the sea's young age, isolation, and the extinction events that occurred during the last glacial maximum (Taviani, 1998). In summary, HEXPLORES targeted the distribution of vents, the role of evaporites vs. magmatism, fluid geochemistry and microbiology, the links between geology and hydrothermal activity, and the nature of vent ecosystems in this understudied ocean basin.

Results and Discussion

During expedition M194, we discovered four new hydrothermally active areas between ~17°N and 25°N (in addition to the Mabahiss and Hatiba Mons sites found in 2023), confirming that active venting is widespread along the Red Sea Rift. All new sites revealed low-temperature vent fields rather than high-temperature black-smoker type vents. The search focused on diverse rift settings; however, all confirmed vent sites were located on the larger axial volcanoes, where fault-controlled pathways channel hydrothermal flow to the seafloor. Even though only a fraction of the Red Sea rift could be covered during M194, the discovery of multiple vent areas strongly suggests that hydrothermal activity at this ultraslow ridge is more frequent than predicted by global models, likely due to the Red Sea's elevated heat flow. Interestingly, even the magma-rich southern segment of the rift (influenced by the Afar hotspot) showed only low-T venting rather than any high-T systems, suggesting this style of hydrothermalism is widespread in the Red Sea's current stage.

At Hatiba Mons – the largest axial volcano in the Red Sea Rift – venting is dominated by an extensive field of Fe-rich microbial mounds that cover an area of ~1.6 km², making it the largest vent field known from any slow or ultraslow ridge (van der Zwan et al., 2023; Diercks et al., 2025). Gravity coring and mineralogical analyses revealed not only Fe- and Mn-oxyhydroxides but also sphalerite, pyrite, barite, and anhydrite at 2–3 m depth – the first direct evidence of massive sulfide mineralization at Hatiba Mons. Fluid inclusion studies indicate that these deposits formed from much hotter fluids in the past (~300°C) compared to the present low-T venting (<60 °C). This shows that Hatiba Mons has undergone a dynamic hydrothermal history, with earlier high-temperature phases leaving behind mineralized ore bodies now capped by microbial mats (Diercks et al.,

2025). The unusual chemistry of these deposits also reflects interaction with Miocene evaporites, which likely enhanced metal solubility and contributed to the distinctive Red Sea mineral signatures (Diercks et al., 2025).

Although no active 300°C vents were found at any site during M194, the up to 60°C vent fluids still produce significant mineralization. Iron- and manganese-oxyhydroxide deposits are ubiquitous, forming large Fe-mounds. The discovery of CO₂-rich hypersaline brine pools atop Mabahiss and Hatiba Mons adds an additional discovery of a potential new type of Red Sea brine. These perched volcanic brines, with salinities way above 60‰ and temperatures of 23 to 28°C, possibly represent the volcanic endmember to the well-known axial brine deeps, such as in Atlantis II, and reveal the wide-reaching influence of the evaporites in the Red Sea rift (e. g. van der Zwan et al., 2023, 2024, 2025).

In the southern Red Sea (at ~17°N), the morphology of the rift axis differs markedly from the deep, fault-bounded basins of the central and northern rift. Here, the rift is shallower and characterized by a larger number of cone-shaped volcanoes, reflecting enhanced magmatism linked to the Afar plume (Thomaidis et al., 2024). Ramad Seamount and the adjacent Sesame Cone rise to 260m below the sea level, and rock and precipitate samples collected from the southern sites show a distinct geochemical signature compared to northern Red Sea vents. Basalts recovered from Ramad and Sesame Cone are transitional to alkaline in composition, supporting a plume influence on magmatism in this part of the rift (Thomaidis et al., 2024).

ROV dives confirmed that both edifices also host abundant hydrothermal venting. Fluids are discharged as clear, shimmering water at very low temperatures <30°C, often associated with Fe-oxide chimneys and microbial mats. Visual observations at Sesame Cone showed higher currents, and many vent outlets were rather small holes in the seafloor instead of chimneys. Larger microbial mats at this location were only observed on the lee side in the “wind shadow” of the cone. Hydrothermal deposits were dominated by silica-rich crusts and amorphous precipitates but contained very low concentrations of base metals such as zinc and copper. This contrasts with the metal-enriched deposits found at Mabahiss and Hatiba Mons in the north and central Red Sea and might highlight an along-axis gradient, which needs to be confirmed, though (van der Zwan et al., 2024).

The vent sites documented during M194 were dominated by striking microbial mats forming thick, flocculent blankets on chimneys and surrounding rocks and sediments. These mats were abundant across all active vents and represent the primary visible biomass, sustained by chemosynthetic production. In contrast, macrofauna were extremely sparse. No typical hydrothermal vent megafauna, such as tubeworms, mussels, or clams, was present. Instead, the microbial mats formed the ecological foundation, with only a few opportunistic macrofauna,

including small polychaetes, amphipods, and scattered other invertebrates, observed directly on or near the mats at sites such as Mabahiss Mons.

The scarcity of vent-endemic fauna reflects both the physicochemical constraints of the Red Sea and its biogeographic isolation. The vent fluids sampled during M194 were low in sulfide, limiting the energy available for sulfur-based symbioses that typically support dense vent animal communities elsewhere. At the same time, the Red Sea's elevated salinity and temperature seem to place additional stress on potential colonizers. As a result, the ecosystem remains dominated by microbial primary producers, with only a thin upper trophic layer of opportunists. Samples of microbial mats and fauna were collected for post-cruise genomic and taxonomic analyses, which will help clarify the metabolic strategies that allow life to persist under these extreme conditions (Linse et al., 2024).

In addition to hydrothermal observations, M194 encountered a colonized wood fall on the seafloor. This sunken log supported a reducing-habitat community with diverse macrofauna, including bivalves (likely wood-boring *Xylophaga*), polychaetes, and other small invertebrates. The wood fall provided a striking contrast to the hydrothermal sites: while the vents remain dominated by microbial life with very few observed animals, the wood fall showed that other types of reducing habitats in the Red Sea can sustain richer faunal assemblages (Linse et al., 2024).

In summary, despite the absence of locating high-temperature vents, M194 HEXPLORES achieved its objectives. It revealed multiple new vent systems along the rift, showed that the Red Sea Rift harbors more extensive hydrothermal activity than previously recognized, and demonstrated how evaporite-blanketed crust and magmatism interact to produce unique vent fluid chemistries and mineralization styles. Hatiba Mons illustrates the Red Sea's complex hydrothermal evolution, bridging past high-T venting with present microbial-dominated systems. These discoveries highlight the Red Sea as an important natural laboratory for studying hydrothermal processes in nascent ocean basins, with implications ranging from ore deposition to the origins of life.

Outlook

Samples and datasets collected during M194 are still undergoing detailed post-cruise analyses. Geochemical and mineralogical work will better constrain subseafloor processes and the role of evaporites in shaping fluid composition. Microbiological and genomic studies will clarify the metabolic potential of vent microbial communities and their role in mineral precipitation. Taxonomic analyses of collected fauna, though limited, will expand baseline knowledge of Red Sea biodiversity and support ongoing conservation efforts (Macrina et al., 2025).

The expedition demonstrated that a multidisciplinary approach is critical for understanding such complex, extreme environments. Future work needs to target unresolved questions: Are high-temperature vents present? How do Red Sea vent systems evolve over time? And how do biological communities assemble in such isolated and extreme habitats? By starting to answer these questions, HEXPLORES contributes to the global understanding of hydrothermal systems and illustrates the value of modern research vessels for discovery in Earth's least explored regions.

References

Augustin N, van der Zwan FM, Devey CW, Ligi M, et al., Geomorphology of the central Red Sea Rift: Determining spreading processes, *Geomorphology* 2016, 274, 162–179, doi: 10.1016/j.geomorph.2016.08.028.

Augustin N, van der Zwan FM, Devey CW & Brandsdóttir B, 13 million years of seafloor spreading throughout the Red Sea Basin, *Nature Communications* 2021, 12, 2427, doi: 10.1038/s41467-021-22586-2.

Diercks I, Augustin N, Petersen S, Follmann J, et al., Discovery of dynamic, high-temperature hydrothermalism and massive sulfide formation at Hatiba Mons volcano, Central Red Sea, *Proceedings of the Status Conference Research Vessels 2026* (this volume).

Linse, K, Augustin N & van der Zwan FM, HEXPLORES Expedition Team, HEXPLORES: Secrets of the Red Sea Rift, *Deep-Sea Life* 2024, Issue 22, pp 2–3, <https://www.dosi-project.org/deep-sea-life-issue-22/>.

Macrina L, Terraneo TI, McFadden CS, Chimienti G, Marchese F, et al., The hidden diversity of Saudi Arabian Red Sea octocorals revealed through a morpho-molecular assessment across bathymetric and latitudinal gradients, *Nature Scientific Reports* 2025, in press.

Preine J, Augustin N, Mitchell NC, van der Zwan FM, et al., Tracing the Neovolcanic zone along the sediment-covered regions of the Red Sea Rift, *Scientific Reports* 2025, 15, 5481 doi: 10.1038/s41598-025-89332-2.

Schmidt M, Al-Farawati R & Botz R, Geochemical Classification of Brine-Filled Red Sea Deeps, in: *The Red Sea* 2015 Springer Berlin Heidelberg, pp. 219–233, doi: 10.1007/978-3-662-45201-1_13.

Taviani M, Post-Miocene reef faunas of the Red. In: Purser BH, Bosence DWJ (Eds), *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden* 1998, ISBN 0412 73490 7.

Thomaidis K, van der Zwan FM, Pandey O, Follmann J, et al., Southern Red Sea Volcanism: Afar Plume Influence on Geochemistry and Seafloor Morphology, AGU Abstracts 2024, V51E-3118.

van der Zwan FM, Augustin N, Petersen S & Altalhi SM, Hydrothermal activity in the Red Sea Rift: Discovery and observations of the first active hydrothermal vent fields, AGU Abstracts 2023.

van der Zwan FM, Augustin N, Petersen S, Altalhi SM, et al., Widespread diffuse venting and large microbial iron-mounds in the Red Sea, *Communications Earth and Environment* 2023, 4, 496, doi: 10.1038/s43247-023-01169-7.

van der Zwan FM, Diercks I, Petersen S, Sander SG, et al., Hydrothermal activity in a young ocean—the discovery of six active hydrothermal vent field areas along the Red Sea Rift, *Goldschmidt Conference Abstracts* 2024.

van der Zwan FM, Augustin N, Petersen S, Sander SG, et al., Volcanic, CO₂-rich Brines in the Red Sea: Discovery of a Hydrothermal Endmember?, *Goldschmidt Conference Abstracts* 2025.

van der Zwan FM, Augustin N, Petersen S, Sander SG, et al., Volcanic Brine Pools in the Red Sea Rift: A New Expression of Hydrothermal Activity, AGU Abstracts 2025.

Scientific Output

List of Publications

Macrina L, Terraneo TI, McFadden CS, Chimienti G, Marchese F, Vimercati S, Vicario S, Reimer JD, Purkis SJ, Eweida AA, Pieribone V, Qurban M, Duarte CM, Rodrigue M, van der Zwan FM, Augustin N, Westphal H & Benzoni F, The hidden diversity of Saudi Arabian Red Sea octocorals revealed through a morpho-molecular assessment across bathymetric and latitudinal gradients, *Nature Scientific Reports* 2025, in press.

Linse, K, Augustin N & van der Zwan FM, HEXPLORES Expedition Team, *HEXPLORES: Secrets of the Red Sea Rift*, *Deep-Sea Life* 2024, Issue 22, pp 2–3, <https://www.dosi-project.org/deep-sea-life-issue-22/>.

List of conference presentations

2025 | **Volcanic Brine Pools in the Red Sea Rift: A New Expression of Hydrothermal Activity** AGU Fall Meeting, New Orleans, USA

2025 | **Volcanic, CO₂-rich Brines in the Red Sea: Discovery of a Hydrothermal Endmember** Goldschmidt Conference, Prague, Czech Republic

2025 | **Hydrothermal activity along the young, ultra-slow spreading Red Sea Rift – an update from recent discoveries** EGU General Assembly, Vienna, Austria

2024 | **Southern Red Sea Volcanism: Afar Plume Influence on Geochemistry and Seafloor Morphology** AGU Fall Meeting, Washington D.C., USA

2024 | **Hydrothermal activity in a young ocean–the discovery of six active hydrothermal vent field areas along the Red Sea Rift** Goldschmidt Conference, Chicago, USA

2023 | **Hydrothermal Activity in the Red Sea Rift: Discovery and Observations of the first active Hydrothermal Vent Fields** AGU Fall Meeting, San Francisco, USA

Data

Multibeam raw data (EM122):
<https://doi.org/10.1594/PANGAEA.968520>

Multibeam raw data (EM710):
<https://doi.org/10.1594/PANGAEA.968621>

ADCP current data (38 kHz):
<https://doi.org/10.1594/PANGAEA.965955>

Cruise Report

M194: https://doi:10.48433/cr_m194

M195

Climate Dynamics and Ecosystem Change during the Rise of Mediterranean Civilizations (CYRTACI)

Authors

Institute of Earth Sciences, Heidelberg University | Heidelberg, Germany

J. Pross, A. Bahr, O. Friedrich, A. Koutsodendris

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

D. Nürnberg

Since the Paleolithic, Mediterranean cultures have closely interacted with their environment. However, it is still unclear to what extent climatic and environmental changes have influenced their evolution. Likewise, the onset, early extent, and consequences of anthropogenic change in terrestrial and notably in marine ecosystems are still poorly constrained.

In response to these knowledge *gaps*, R/V METEOR Expedition M195 (CYRTACI – Climate Dynamics and Ecosystem Change during the Rise of Mediterranean Civilizations) aimed to investigate potential interactions between climatic and environmental forcing and sociocultural evolution in the Eastern Mediterranean during the Holocene and latest Pleistocene. This region provides an exceptional natural laboratory for exploring such linkages: it is highly sensitive to abrupt climatic perturbations due to its intermediate position between the climate systems of the higher (influenced by the westerlies and outbreaks of the Russian High) and lower (i. e., monsoonally influenced) latitudes, and it preserves an unparalleled archeological and paleoenvironmental record of prehistoric to historic cultures in coastal and near-coastal settings.

Expedition M195 represented a direct and complementary follow-up to Expedition M144, which had explored parts of the Aegean, Ionian, and Adriatic Seas in December 2017–January 2018. To obtain sedimentary archives suitable for high-resolution land-based investigations, 205 m of gravity cores from 38 stations and 33 m of kasten cores from nine stations were recovered from extremely proximal

settings with particularly high sedimentation rates in the Aegean, Ionian, and Libyan Seas (Pross et al., 2024). These efforts sought to lay the groundwork for a spatiotemporally resolved reconstruction of climatic and environmental changes across marine and terrestrial ecosystems during the rise of Eastern Mediterranean civilizations.

The selected research areas, located exclusively within the Greek Exclusive Economic Zone and territorial waters (within the six-mile zone in the Aegean and the twelve-mile zone in the Ionian Sea), were chosen to maximize the likelihood of recovering continuous, high-sedimentation Holocene and Lateglacial sequences. Coring stations were determined through detailed hydroacoustic surveys, partly informed by previous work of Greek collaborators at the Hellenic Center for Marine Research (HCMR). Each research area followed a standardized work program comprising CTD casts, multicorer (MUC) deployments for surface-sediment sampling – particularly for proxy calibration and geochemical characterization of upper seafloor sediments – and gravity and Kasten coring to recover long, continuous, and voluminous sedimentary archives. Onboard color scanning provided preliminary stratigraphic control, notably through the identification of Sapropel S1. Finely laminated, possibly varved sediments were obtained from both the Epidavros Basin – a paleolake isolated from the open Aegean during the Last Glacial sea-level lowstand – and the modern anoxic setting of the Gulf of Amvrakikos. Sediment cores from the Epidavros Basin (six gravity cores up to 9.3 m in length, one Kasten core of 5.8 m, and 32 multicorer cores) are arguably particularly noteworthy. They reveal two main lithological units: Unit I, composed of non-laminated greenish-grey silt and clay, represents fully marine deposition during Marine Isotope Stage (MIS) 3 and the Holocene. Unit II, typically occurring in the middle of the succession, consists of finely laminated silt and clay with 1–2 mm alternations of white (calcite- and aragonite-rich) and dark layers, indicating deposition in a restricted coastal environment. The succession also contains a dark green, organic-rich silt/clay layer up to 0.5 m thick, intercalated within the laminated intervals, as well as at least two macroscopically visible tephra layers.



Figure 1: Example of finely laminated (potentially varved) sediments retrieved from the Epidavros Basin. Photo credit: Jörg Pross.

Following the cruise, all cores underwent X-ray fluorescence (XRF) scanning at the Institute of Earth Sciences, Heidelberg University. The resulting element-geochemical data, combined with radiocarbon dates from the core bases, enabled preliminary correlations with published records and provided initial age constraints. These analyses revealed extremely high sedimentation rates (up to approximately 6 m/ka) in nearshore settings and sequences extending into the Last Glacial (~50 ka) in more distal locations. A key chronological marker readily identifiable in most cores is the anthropogenic lead pollution peak that marks the onset of Roman occupation of Ancient Greece around 2150 years BP (Koutsodendris et al., 2025).

Based on these preliminary age models, members of the M195 Science Party have sampled the cores for a wide range of analyses, including palynology, benthic and planktic foraminifera, ostracods, diatoms, and inorganic and organic geochemistry. Additional radiocarbon dating is currently underway. Together with tephra marker horizons and the anthropogenic Pb peak, these data will enable the construction of high-resolution chronological frameworks, allowing for precise temporal integration of the developing multiproxy datasets.

References

Koutsodendris A, Maran J, Kotthoff U, Bahr A, Friedrich O, Gerdes A, Kaboth-Bahr S, Knipping M, Lippold M, Sakellariou D, Schulz H & Pross J, Societal changes in Ancient Greece impacted terrestrial and marine environments, *Communications Earth & Environment* 2025, 6, doi: <https://doi.org/10.1038/s43247-024-01921-7>.

Pross J, Bahr A, Bauersachs T, Berke M, Blanchet C, Bubenzer O, Ehmke Espinoza I, Evers F, Friedrich O, Gerber L, Glos M, Gurrer D, Hecht S, Herz F, Köhler N, Kolb L, Kotthoff U, Koutsodendris A, Müller D, Paraschos F, Perrakis S, Raeke A, Rheinberger S, Sakellariou D, Schmickal S, Unkel I, Waldhör E & Wu F, Climate Dynamics and Ecosystem Change during the Rise of Mediterranean Civilizations, Cruise No. M195, November 11 – December 02, 2023, Piraeus – Piraeus (Greece), METEOR-Berichte 2024, M195, 1, 1-43, DOI: https://doi.org/10.48433/cr_m195.

Scientific Output

List of Publications

Koutsodendris A, Maran J, Kotthoff U, Bahr A, Friedrich O, Gerdes A, Kaboth-Bahr S, Knipping M, Lippold M, Sakellariou D, Schulz H & Pross J, Societal changes in Ancient Greece impacted terrestrial and marine environments, Communications Earth & Environment 2025, 6, doi: <https://doi.org/10.1038/s43247-024-01921-7>.

List of conference presentations

2024 | **Changes in Holocene sediment deposition in the Aegean Sea: climatic versus early anthropogenic forcing** European Geosciences Union, Vienna, Austria

Data

Master track:

<https://doi.org/10.1594/PANGAEA.967481>

Thermosalinograph oceanography:

<https://doi.org/10.1594/PANGAEA.971725>

Multibeam bathymetry:

<https://doi.org/10.1594/PANGAEA.968514>

Cruise Report

M195: https://doi.org/10.48433/cr_m195

M196

Gulf of Corinth Groundwater – Is the deep offshore freshened groundwater body within the Gulf of Corinth actively recharging?

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

M. Jegen, A. Haroon, T. Mueller, M. Schmidt

University of Hawai'i | Honolulu, USA

A. Haroon

BGR, Federal Institute for Geosciences and Natural Resources | Cottbus, Germany

T. Mueller

Hellenic Centre of Marine Research | Athens, Greece

M. D. Sakellariou⁴

University of Malta | Malta

M. Giona Bucci, S. Horozal

BGR, Federal Institute for Geosciences and Natural Resources | Hannover, Germany

K. Schwalenberg

University of Patras | Patras, Greece

D. Christodoulou

and M196 research team members.

Coastal regions host nearly 2.4 billion people living within 100 km of the shoreline, where population densities far exceed the global average. These zones face escalating stress on their groundwater resources, leading to declining water quality (Trevett, Carter & Tyrrel 2004), land subsidence (Galloway & Burbey 2011), and increasing dependence on costly alternative water-supply technologies such as desalination (Elimelech & Phillip 2011). In response, researchers have

turned toward unconventional freshwater reservoirs, including offshore freshened groundwater (OFG) – low-salinity water stored within the pore spaces of sediments beneath the seafloor (Post et al. 2013; Bakken et al. 2012; Micallef et al. 2021). Global estimates suggest that OFG may contain centuries' worth of extractable freshwater (Post et al. 2013), positioning it as a potentially important resource to help alleviate pressure on coastal aquifers during periods of reduced recharge. Yet despite this potential, OFG systems remain poorly characterized: early work relied mostly on sparse borehole data, and only in the past five years have detailed spatial studies begun to reveal their distribution (e. g., Gustafson et al., 2019; Haroon et al., 2021; Faghih et al. 2024 & 2025). The mechanisms governing OFG formation, persistence, and interaction with terrestrial aquifers remain insufficiently understood, impeding assessments of sustainable exploitation.

To address these knowledge gaps, the Helmholtz-funded SMART project – an international partnership between GEOMAR and the University of Malta – sought to combine geophysical mapping and geochemical analysis to detect, quantify, and characterize OFG systems in the Mediterranean Sea. Initial work offshore Malta yielded promising geophysical results indicative of OFG (Haroon et al. 2021; Faghih et al. 2025). However, the hard carbonate seafloor prevented successful gravity coring, and no pore-water samples could be retrieved for geochemical analysis. Furthermore, all bathymetric features suspected of active seepage were ultimately determined to be unrelated to groundwater discharge, precluding direct sampling of OFG fluids and limiting interpretations regarding their origin and dynamics. To meet SMART's objectives, we shifted focus to a site with known OFG occurrences: the Gulf of Corinth, Greece.

The Gulf of Corinth contains substantial freshened pore waters linked to its active rift setting and alternation between marine and lacustrine depositional environments. During past sea-level lowstands, the Gulf evolved into a largely isolated fresh- to brackish-water lake, allowing low-salinity waters to infiltrate and become trapped in the subsurface (Horozal et al., 2025). IODP Expedition 381 (McNeil et al. 2019) documented pore-water salinities as low as 3–10 PSU within both lacustrine and marine sediments, demonstrating that deep units can retain relict freshwater despite prolonged seawater exposure. These findings raise key questions about the hydrogeological and stratigraphic mechanisms that preserve such fluids and about the extent to which present-day or paleo-hydrologic processes contribute to OFG maintenance. The presence of multiple seafloor seepage features along the southwestern Gulf margin further underscores the complexity of subsurface flow pathways.

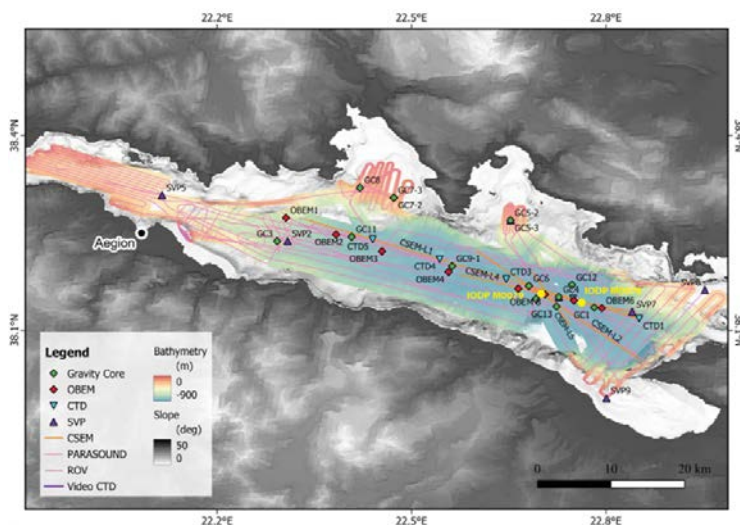


Figure 1: Overview of M196 stations. Bathymetric data acquired on M196 is shown as a color map, cruise track as orange lines. OBEM refers to sites occupied by ocean bottom electromagnetic instruments, CSEM to controlled source electromagnetic profile lines, CTD to vertical conductivity/temperature/depth profiles sites, Video-CTD to conductivity/temperature/depth and video seafloor profiles. SVP to vertical velocity profile measurements, parasound to high frequency acoustic data acquisition profiles and ROV to mini remote operated vehicle data acquisition. Also shown are the gravity coring (GC) sites.

Research cruise M196 conducted an integrated geophysical–geochemical investigation to delineate the distribution, origin, and dynamics of OFG within the Gulf of Corinth (Figure 1). Geophysical operations included multibeam bathymetry, parasound profiling, and high-resolution controlled-source electromagnetic (CSEM) surveying complemented by marine magnetotelluric (MT) measurements. Because electrical resistivity is directly sensitive to pore-water salinity, electromagnetic methods are central to OFG exploration. Converting resistivities into salinity estimates requires independent constraints on lithology and porosity; for this purpose, existing seismic surveys were incorporated. Technical issues limited CSEM acquisition to two profiles (L4 and L1), but both intersect IODP boreholes, allowing future resistivity inversions and salinity models to be validated against measured pore-water data. Analysis of the electromagnetic dataset is ongoing.

Approximately 1,135 km² of seafloor were mapped with multibeam and parasound, yielding 45% coverage of the entire Gulf and extending earlier bathymetric surveys both eastward and westward. The bathymetric dataset will be integrated with onshore topography for tectonic geomorphology analyses, a crucial step in reconstructing sea-level variations and associated OFG formation stages. Particular emphasis in the parasound data lies on identifying mass-wasting deposits, which typically exhibit enhanced hydraulic conductivity and may act as preferential pathways or reservoirs for freshened groundwater. These acoustic datasets have been transferred to the University of Malta for detailed analysis.

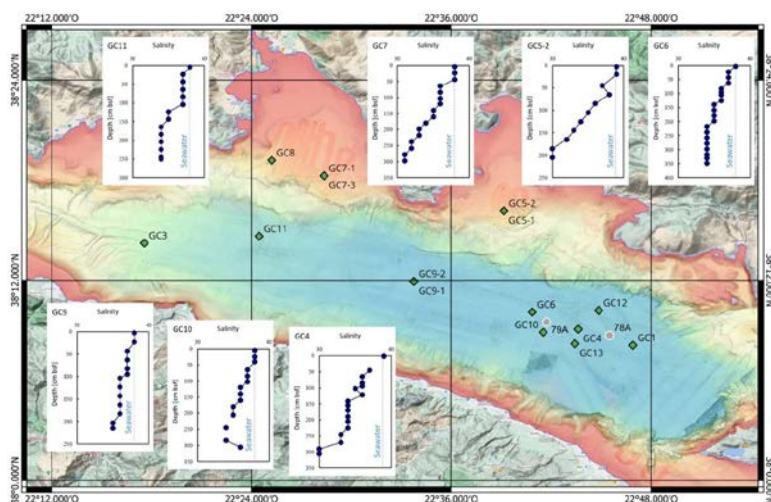


Figure 2: Preliminary results of pore water salinity variations within gravity cores.

Geochemical analyses of pore waters from gravity cores provide robust confirmation of widespread OFG (Figure 2). Most cores show decreasing chloride concentrations with depth, consistent with a transition from marine to increasingly freshened pore waters. This pattern, first identified at IODP Sites M0078 and M0079 (McNeil et al. 2019), is reproduced across nearby cores and extends into deeper central basin sediments (~850 m water depth). Only GC 1, east of the IODP boreholes, shows uniform chloride profiles, highlighting local variability in lithology or fluid flow. Stable isotope measurements offer further insights: pore-water $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values are consistently depleted relative to seawater and plot left of the global seawater line, indicating mixing with an isotopically lighter meteoric endmember. Modern precipitation from the Patras and Athens regions exhibits similar depletion, suggesting that the freshened pore waters represent paleo-meteoric recharge during lacustrine phases. The variability of porewater freshening in the GoC obviously records the history of marine-lacustrine transitions as modelled by Müller et al., (subm.). Further model simulations including M196 and IODP data will be conducted using a transport-reaction model (Schulten et al. subm.) combined with 2D-paleo-hydrochemical modelling (Sheng et al., 2025).

The preliminary M196 datasets indicate that OFG in the Gulf of Corinth forms a regionally extensive groundwater system rather than a localized anomaly. The persistence of low-salinity fluids across both lacustrine and marine sequences indicates that paleoenvironmental trapping, structural controls, and possibly ongoing recharge all contribute to OFG maintenance. The planned transport-reaction modelling, combined with IODP results and new resistivity inversions, will refine estimates of OFG volume, geometry, and residence times. These

findings will improve understanding of the processes governing OFG preservation in active rift basins and contribute to global assessments of OFG as a potential supplementary freshwater resource.

References

Bakken H, Ruden F, Mangset LE, Submarine groundwater: A new concept for the supply of drinking water, *Water Resources Management* 2012, 26, 1015–1026.

Elimelech M & Phillip W, The future of seawater desalination: energy, technology, and the environment, *Science* 2011, 333, 712–717.

Faghih Z, et al., Characterizing offshore freshened groundwater salinity patterns using trans-dimensional Bayesian inversion of controlled source electromagnetic data: A case study from the Canterbury Bight, New Zealand, *Water Resources Research* 2024, 60.3: e2023WR035714.

Faghih Z, et al., Investigation of offshore freshened groundwater using marine controlled–source electromagnetic: Insights from Gozo, Maltese Islands, *Journal of Applied Geophysics* 2025, 105842.

Galloway D & Burbey T, Regional land subsidence accompanying groundwater extraction (Review), *Hydrogeology Journal* 2011, 19, 1459–1486.

Gustafson C, Key K & Evans RL, Aquifer systems extending far offshore on the U.S. Atlantic margin, *Sci. Rep.* 2019, 9, 8709.

Horoza S, Micallef A, De Biase M, et al., Geological and sea level controls on offshore freshened groundwater in a rift basin: Gulf of Corinth, Greece, *Hydrogeol J* 2025, <https://doi.org/10.1007/s10040-025-02943-x>.

Haroon A, Micallef A, Jegen M, Schwalenberg K, Karstens J, Berndt C, Garcia X, Kühn M, Rizzo E, Fusi NC, Ahaneku, Petronio L, Faghih Z, Weymer BA, De Biase M & Chidichimo F, Electrical Resistivity Anomalies Offshore a Carbonate Coastline: evidence for Freshened Groundwater?, *Geophys. Res. Lett.* 2021, 48 (14), Article e2020GL091909, [10.1029/2020GL091909](https://doi.org/10.1029/2020GL091909).

McNeill LC, Shillington DJ, Carter GDO, Carter, & the Expedition 381 Participants (2019), *Proceedings of the International Ocean Discovery Program Volume 381* publications.iodp.org.

Micallef A, Person M, Berndt C, Bertoni C, Cohen D, Dugan B, Evans R, Haroon A, Hensen C, Jegen M, Key K, Kooi H, Liebetrau V, Lofi J, Maillux BJ, Martin-Nagle R, Michael HA, Müller T, Schmidt M, Schwalenberg K, Trembath-Reichert E, Weymer B, Zhang Y & Thomas AT, Offshore freshened groundwater in continental margins, *Reviews of Geophysics* 2021, 59, e2020RG000706.

Müller T, Hensen C, Sheng C, Haroon A, Sakellariou D, Bekaert V & Schmidt M, Freshened Groundwater formation underneath the Gulf of Corinth – Insights from numerical modelling, submitted to *Journal of Geophysical Research: Oceans*.

Post VEA, Groen J, Kooi H, Person M, Ge G & Edmunds WM, Offshore fresh groundwater reserves as a global phenomenon, *Nature* 2013, 504, pg. 71–78.

Sheng C, Micallef A, Schmidt M, Müller T, Hensen C, Unravelling groundwater salinization and flushing in the Canterbury Bight during glacial-interglacial cycles: Insights from paleo-hydrogeochemical, *EGU General Assembly 2025*, 25-4809. doi.org/10.5194/egusphere-egu25-4809.

Schulten I, Maselli V, Hensen C, Berndt C, Schmidt M, Müller T, Micallef A, Brown C, Haeckel M, van Geldern R, Elger J, Hölz S, Córdoba-Ramírez F, Kurylyk B, Yu S & Nedimović M, Can offshore freshened groundwater drive sediment deformation?, submitted to *GEOLOGY*.

Trevett AF, Carter R & Tyrrel S, A study of household drinking water quality in rural Honduras, *International Journal of Environmental Health Research* 2004, Vol. 14(4), 273–283.

Scientific Output

Cruise Report

M196: https://doi.org/10.48433/cr_m196

M197

Biogeochemistry of the Wintertime Eastern Mediterranean Sea: results from the M197 expedition

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

T.J. Browning, E.P. Achterberg, Z. Steiner

Introduction

A collaboration of scientists from GEOMAR Helmholtz Centre for Ocean Research Kiel and University of Haifa/Israeli Institute for Ocean and Limnological Research (IOLR, Israel) is working to characterize the past and current chemical and biological status of the Eastern Mediterranean Sea (EMS). The broad aim of this collaboration is to use the region, which hosts seawaters that are warming at amongst the fastest rates on Earth, as a natural laboratory to understand future potential biogeochemical changes in the wider low latitude subtropical oceans. These efforts are supported by a Helmholtz International Laboratory, the 'Eastern Mediterranean Sea as a model for Future Ocean Research (EMS-FORE)'.

The research cruise M197 was conducted in order to characterize baseline wintertime biogeochemical conditions of the EMS. The original aim of this expedition included a detailed investigation of seawaters and sediments off the coast of Israel; however, this was not possible (at short notice) due to the start of the conflict in the region (October 2023). The cruise programme was rapidly adapted to focus research in waters further to the west. The following objectives were pursued: (i) characterizing nutrient biogeochemistry and phytoplankton nutrient limitation of seawaters in the EMS, (ii) documenting in detail the microbial communities that inhabit these waters from the surface ocean to sediments, (iii) assessing mechanistic connections between nutrient biogeochemistry, surface ocean productivity, deeper water metabolism, and shelf sediments in the cycling of carbon and major nutrients, (iv) using the sedimentary record to assess past environmental change in the EMS.

Methods

The research cruise M197 with the RV METEOR sailed January 6th 2024 to February 6th 2024 from Limassol (Republic of Cyprus) to Catania (Italy). On the research cruise, 30 stations were occupied. Station locations were determined on the basis of achieving good spatial coverage as well as capturing multiple permanent eddy features that characterize the region. Seawater samples were collected from the surface to the seafloor to measure chemical properties of the seawater, including major and trace nutrients, the carbonate system, microplastics, and the microbial communities inhabiting the water column. Experiments were conducted to assess rates of primary production and nitrogen fixation, and the nutrients regulating phytoplankton growth. Sinking carbon fluxes were determined using the thorium-234 approach. The types and abundance of zooplankton were determined via various nets and two camera systems. The deposition flux and chemistry of aerosols was also assessed. Sediment cores were collected to determine nutrient fluxes into the overlying water column as well as investigate past environmental conditions.

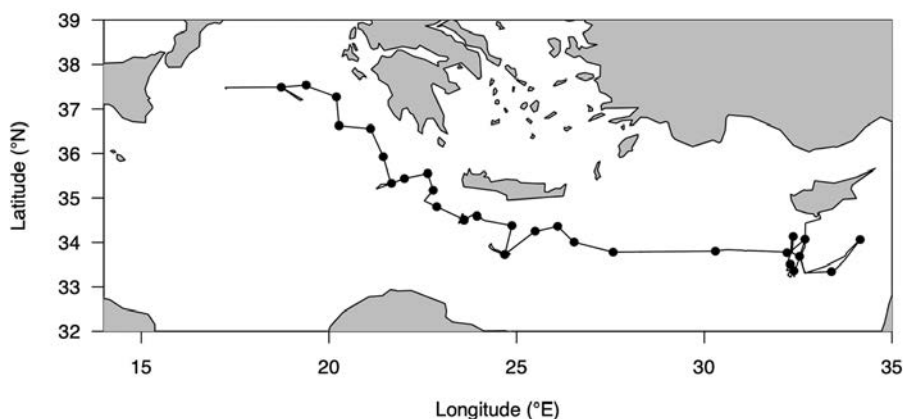


Figure 1: Map of sampling sites on M197.

Results and Discussion

Overall sea surface temperatures and salinities decreased from east to west, consistent with climatological geographic variability. Superimposed on this broad trend were clear shifts on transitioning through the multiple, semi-permanent eddies that occupy this portion of the Eastern Mediterranean. An important feature of the research cruise were periodic, transient storm events, which led to mixed layer depth deepening and impacted the overall biogeochemistry of the upper water column. Overall mixed layer depths ranged from ca. 20 m through to >130 m depth.

The upper water column (ca. 0–150 m depth) remained depleted in the macronutrients nitrate and phosphate throughout the entire cruise transect. Whilst remaining overall very low, phosphate concentrations in the upper ca. 200 m showed a broad-scale east to west trend of increasing values. Dissolved trace elements were in general strongly elevated throughout the water column in comparison to typical open ocean concentrations. This was due to (i) high supplies to the surface via dust deposition (including major Saharan dust deposition events during the expedition), alongside (ii) the close proximity to coastlines and shallow bathymetry, and enclosed nature of the basin.

Phytoplankton concentrations (as indicated by chlorophyll-a as well as overall particulate organic carbon) remained relatively low throughout, with a weak increasing trend from east to west. Phytoplankton community structure was generally mixed with relatively high contributions of haptophytes (as indicated by analysis of phytoplankton diagnostic pigments). Nutrient addition bioassay experiments demonstrated phytoplankton communities were either nitrogen limited or nitrogen-phosphorus co-limited, consistent with observations previously made in the summertime (Tanaka et al., 2011). Indeed, rates of alkaline phosphatase were strongly elevated in near-surface waters, suggesting a strong reliance of microbial communities on utilizing dissolved organic phosphorus sources for growth.

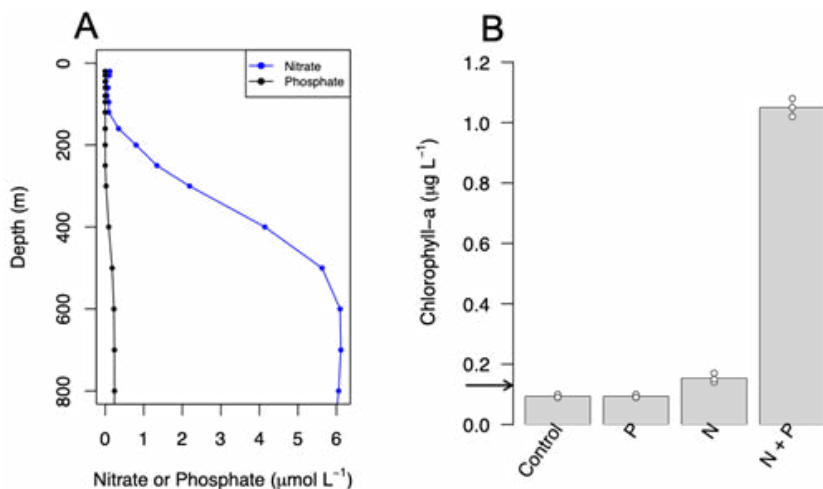


Figure 2: (A) Characteristic nutrient profiles showing strong nitrate and phosphate depletion in surface waters. (B) Example phytoplankton (as indicated by chlorophyll-a) response to nutrient supply showing restricted responses to nitrogen (N) or phosphate (P) alone, and greater response to combined nitrogen and phosphate (N+P) supply. Results are at day 5 of the incubation period. Arrow indicates initial concentrations.

Transects performed with video observations revealed gelatinous zooplankton taxa in the wintertime EMS had low abundance and diversity in comparison to other open ocean regions, which was likely linked to the low surface primary productivity. Sinking particle fluxes (as indicated by ^{234}Th activities) were also relatively low, again owing to the low productivity of overlying waters. Despite potentially driving modifications to nutrient supply rates to surface waters, no distinct impact of cyclonic or anticyclonic eddies were found on particle export. The character of sinking particles however showed regional differences, with larger, silica-rich particles being more abundant in the west, while smaller, organic-rich particles dominated to the east. The broadscale pattern in surface pCO₂ was an east-to-west decrease that could predominantly be attributed to coincident temperature changes.

At the time of writing, many of the sample analyses and data interpretations remain underway.

Reference

Tanaka T, Thingstad TF, Christaki U, Colombet J, Cornet-Barthaux V, Courties C, Grattepanche JD, Lagaria A, Nedoma J, Oriol L and Psarra S, Lack of P-limitation of phytoplankton and heterotrophic prokaryotes in surface waters of three anticyclonic eddies in the stratified Mediterranean Sea, *Biogeosciences* 2011, 8, 525–538, doi:10.5194/bg-8-525-2011.

Scientific Output

List of Publications

Ankri B, Herut B, Velasquez-Dubinski X, Paytan A & Rahav E, Viability of prokaryotes in nascent aerosolized sea spray across the Eastern Mediterranean Sea, *Journal of Geophysical Research (Atmospheres)* 2025, 130, p.e2025JD043340, doi: <https://doi.org/10.1029/2025JD043340>.

List of conference presentations

2025 | **Quantification of Gelatinous Zooplankton Community Structures in Two Contrasting Ocean Regions**, Deep-Sea Biology Symposium, Hong Kong, China

2026 | **Warmer winters enhance ultra-oligotrophy and alter dissolved trace metal cycling in Eastern Mediterranean anticyclones.** Ocean Sciences Meeting, Glasgow, Scotland

2026 | **Quantifying Particle Export in the Eastern Mediterranean Sea.** Ocean Sciences Meeting, Glasgow, Scotland

2026 | **Total Alkalinity Dynamics in the Eastern Mediterranean Sea.** Ocean Sciences Meeting, Glasgow, Scotland

2026 | **Effect of oligotrophication and warming on seafloor benthic fluxes – the Eastern Mediterranean as a natural laboratory.** Ocean Sciences Meeting, Glasgow, Scotland

Data

Physical oceanography:

<https://doi.org/10.1594/PANGAEA.972141>

Sea spray aerosols:

<https://doi.org/10.1594/PANGAEA.974259>

Thermosalinograph data:

<https://doi.pangaea.de/10.1594/PANGAEA.985387>

38 kHz ADCP data:

<https://doi.org/10.1594/PANGAEA.971502>

75 kHz ADCP data:

<https://doi.org/10.1594/PANGAEA.971504>

Multibeam bathymetry data (EM122):

<https://doi.org/10.1594/PANGAEA.969298>

Multibeam bathymetry data (EM710):

<https://doi.org/10.1594/PANGAEA.969303>

Cruise Report

M197: https://doi.org/10.48433/cr_m197

PS124

A Continental Shelf Multidisciplinary Flux Study (COSMUS) of carbon

Authors

Alfred-Wegener-Institute, Helmholtz Centre for Polar- und Marine Research | Bremerhaven/Sylt, Germany

M. Holtappels, A. Rogge, M. Janout, H. Grotheer, L. Oziel, J. Hauck, M. Campos van Caspel, H. Hellmer

Institute for Chemistry and Biology of the Marine Environment, University of Oldenburg | Oldenburg, Germany

T. Dittmar, S. Bercovici

GeoBio-Center, Ludwig Maximilians University (LMU) Munich | Munich, Germany

G. Gomez-Saez

Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam | Amsterdam, Netherlands

C. Nissen

The southern Weddell Sea Shelf

On the southern Weddell Sea continental shelf, sea ice production and deep water formation (Nicholls et al., 2009) coincide spatially with a high seasonal primary production (Arrigo et al. 2008, 2015), which together bears potential for a significant export of biologically fixed CO₂ to greater depth. At the same time, the formation of cold dense water supports the stability of an oceanic front at the continental shelf break, the Antarctic Slope Front (ASF) and hinders the excessive penetration of warm water masses onto the continental shelf (Jacobs, 1991), thus preventing accelerated melting at the Filchner-Ronne Ice Shelf base (Hellmer et al., 2012). The ice shelf itself and the shelf sediments are potential sources of iron, which regulates algae blooms in the Southern Ocean (Monien et al., 2014) and enables the high primary production rates on the continental shelf. In light of unrestrained carbon dioxide emissions and expected warming of the southern ocean, it is necessary to analyse the interdependence of these physical, geochemical, and biological processes and to assess their significance

for global heat and carbon fluxes. With an interdisciplinary team, a comprehensive investigation was conducted, focussing on the ocean heat and mass transport, the coupled nutrient dynamics, and the conditions for biological production in this region. The aim was to (i) assess the potential for future warming of shelf waters and related ice shelf basal melting, (ii) quantify the turnover of the biological carbon pump and understand its regulation, (iii) determine the Antarctic shelf's contribution to global carbon and nutrient budgets, and (iv) assess possible impacts of climate change on the Antarctic ecosystem. Our focus here is exclusively on the carbon budget, and we report on the quantification of carbon sequestration via a coupled biological-physical carbon pump to the deep basins of the Weddell Sea.

RV Polarstern Expedition PS124

Data and samples were collected onboard RV Polarstern between February 3rd and March 30th 2021. Profiles of water mass properties were measured using a CTD equipped with a fluorometer, transmissometer and 24-bottle carousel water sampler. An Underwater Vision Profiler 5hd was attached to simultaneously acquire particle abundance and images. At 85 stations, the various water masses (Figure 1) were probed and samples for suspended particulate matter (SPM), Chlorophyll (Chla), particulate organic carbon and nitrogen (POC, PON), dissolved (in)organic carbon (DOC, DIC) and total alkalinity (TA) were collected and analyzed on shore for respective concentrations. Molecular characterization of dissolved organic matter (DOM) was analyzed using Ultrahigh-resolution Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR-MS) and structural nuclear magnetic resonance (^1H -NMR). For the different carbon fractions ^{14}C -age was analyzed using a Mini Carbon Dating System (MICADAS). A series of oceanographic moorings were recovered (x16) and deployed (x22), providing time series of currents and properties of the different water masses.

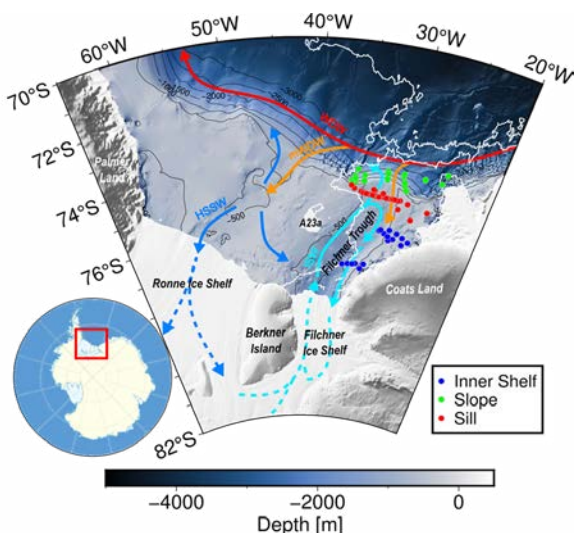


Figure 1: Overview of the southern Weddell Sea shelf and sampling stations (dots) during expedition PS124 (COSMUS). Sampling stations were on the inner shelf (blue), along the sill (red) and at the slope (green) of the continental margin. Important water masses and their pathways are: High Salinity Shelf Water (HSSW), Ice Shelf Water (ISW), Warm Deep Water (WDW) and modified Warm Deep Water (mWDW). Black contours indicate isobaths in 500 m increments. White lines show 60% sea ice concentration to outline the Filchner Trough polynya.

The southern Shelf Carbon Cycle

The samples and measurements were combined to establish a carbon budget of the southern Weddell Sea shelf, addressing air-sea CO_2 fluxes, mixed layer export, and water mass-specific carbon inventories. Air-sea flux of the ice-free areas was determined by (1) pCO_2 gradients (instantaneous flux), (2) DIC and NO_3^- drawdown (seasonally integrated flux) and (3) ^{14}C enrichment (residence time integrated flux). This multi-determined air-sea flux was then related to the differences of carbon concentrations (DIC, DOC, POC) between source water masses and exported water masses at the continental margin. The air-sea flux estimates were then extrapolated to the entire shelf with the help of remote sensing sea-ice concentration data and numerical model outputs. The water mass exchange estimates were extrapolated with the help of numerical models and the multi-year variability of water mass exchange was validated with mooring data.

Our budget indicates an overall net export from the shelf of $\sim 9 \text{ Mt C y}^{-1}$ (Rogge et al. in prep). The exported carbon is primarily composed of remineralized DIC, which was enriched in outflowing dense shelf waters due to its residence time on the shelf. Mooring observations between 2017–2021 confirm regular outflow of dense shelf waters and applying the DIC signatures established during PS124 results in relatively stable excess DIC concentrations in outflowing waters relative to the inflow. This indicates that the southern Weddell Sea shelf is currently

functioning as a stable net carbon sink. The outflow of POC and DOC was found to be of minor importance. Interestingly, the molecular composition of dissolved organic matter (DOM) is highly similar between in- and outflowing water masses, suggesting a rapid and complete consumption of labile organic matter (Gomez-Saez et al. under review at PNAS).

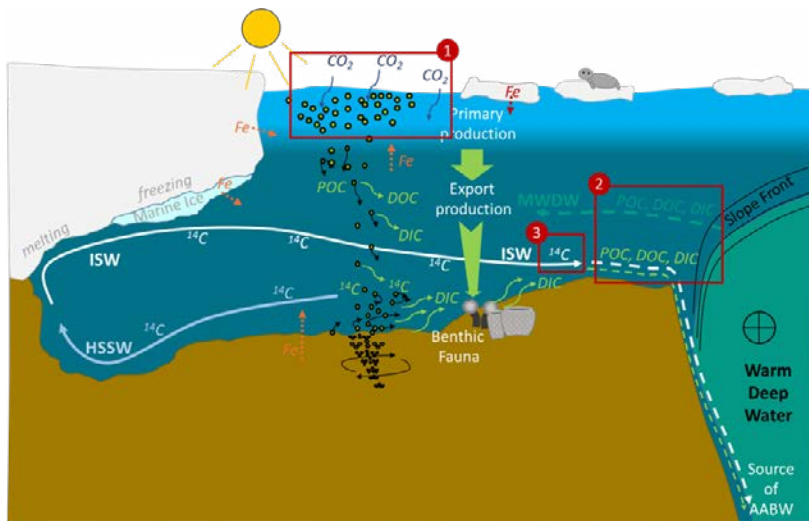


Figure 2: Schematic representation of the study area consisting of Filchner-Ronne Ice Shelf, continental shelf, slope front, and characteristic water masses. Overlaid are transformation processes and transport pathways of the main carbon fractions (POC, DOC, DIC). The red boxes mark the different approaches used to quantify the CO_2 exchange with the atmosphere (box 1), the difference in POC, DOC, and DIC concentrations between inflow via mWDW and outflow via ISW (box 2), and the ^{14}C age of main C fractions circulating on the shelf (box 3).

References

- Arrigo KR, van Dijken GL & Bushinsky S, Primary production in the Southern Ocean, 1997–2006, *J. Geophys. Res.* 2008, 113(C8), doi:10.1029/2007JC004551.
- Arrigo KR, van Dijken GL & Strong AL, Environmental controls of marine productivity hot spots around Antarctica, *J. Geophys. Res.* 2015, 120(8), 5545–5565, doi:10.1002/2015JC010888.
- Hellmer HH, Kauker F, Timmermann R, Determann J & Rae J, Twenty-first-century warming of a large Antarctic ice shelf cavity by a redirected coastal current, *Nature* 2012, 485 (7397), 225–228, doi:10.1038/nature11064.
- Jacobs SS, On the nature and significance of the Antarctic Slope Front, *Mar. Chem.* 1991, 35(1), 9–24, doi:10.1016/S0304-4203(09)90005-6.

Monien P, Lettmann KA, Monien D, Asendorf S, Wölfl A-C, Lim DH, Thal J, Schnetger B & Brumsack HJ, Redox conditions and trace metal cycling in coastal sediments from the maritime Antarctic, *Geochimica et Cosmochimica Acta* 2014, 141, 26–44, doi:10.1016/j.gca.2014.06.003.

Nicholls KW, Østerhus S, Makinson K, Gammelsrød T & Fahrbach E, Ice-ocean processes over the continental shelf of the southern Weddell Sea, Antarctica: A review. *Rev. Geophys.* 2009, 47, RG3003, doi:10.1029/2007RG000250.

Scientific Output

List of Publications

Arndt S, Sensitivity of Sea Ice Growth to Snow Properties in Opposing Regions of the Weddell Sea in Late Summer. *Geophysical Research Letters* 2022, 49(19), e2022GL099653. <https://doi.org/10.1029/2022GL099653>.

Arndt S, Maaß N, Rossmann L & Nicolaus M, From snow accumulation to snow depth distributions by quantifying meteoric ice fractions in the Weddell Sea. *The Cryosphere* 2024, 18(4), 2001–2015, <https://doi.org/10.5194/tc-18-2001-2024>.

Balaguer J, Koch F, Flintrop CM, Völkner C, Iversen MH & Trimborn S, Iron and manganese availability drives primary production and carbon export in the Weddell Sea. *Current Biology* 2023, 33(20), 4405–4414.e4404, <https://doi.org/10.1016/j.cub.2023.08.086>.

Darelius E, Daae K, Dundas V, Fer I, Hellmer HH, Janout M, Nicholls KW, Sallée J-B & Østerhus S, Observational evidence for on-shelf heat transport driven by dense water export in the Weddell Sea. *Nature Communications* 2023, 14(1), 1022, <https://doi.org/10.1038/s41467-023-36580-3>.

Darelius E, Dundas V, Janout M & Tippenhauer S, Sudden, local temperature increase above the continental slope in the southern Weddell Sea, Antarctica, *Ocean Sci.* 2023, 19(3), 671–683. <https://doi.org/10.5194/os-19-671-2023>.

Darelius E, Fer I, Janout M, Daae K & Steiger N, Observations of the Antarctic Slope Current in the Southeastern Weddell Sea: A Bottom-Enhanced Current and Its Seasonal Variability, *Journal of Geophysical Research: Oceans* 2024, 129(6), e2023JC020666. <https://doi.org/10.1029/2023JC020666>.

Egbers PH, Zurhelle C, Koch BP, Dürwald A, Harder T & Tebben J, Selective purification of catecholate, hydroxamate and α -hydroxycarboxylate siderophores with titanium dioxide affinity chromatography, *Separation and Purification Technology* 2023, 307, 122639. <https://doi.org/10.1016/j.seppur.2022.122639>.

Gomez-Saez G, Bercovici S, Renken M, Vemulapalli S, Rogge A, Grotheer H, Holtappels M & Dittmar T, Dissolved organic matter properties are conserved during Weddell Sea deep water formation, under review at PNAS.

Joshi M, Mestas-Nuñez AM, Ackley SF, Arndt S, Macdonald GJ & Haas C, Seasonal and Interannual Variations in Sea Ice Thickness in the Weddell Sea, Antarctica (2019–2022) Using ICESat-2. *Remote Sensing* 2024, 16(20).

Laget M, Drago L, Panaïotis T, Kiko R, Stemmann L, Rogge A, Llopis-Monferrer N, Leynaert A, Irisson J-O & Biard T, Global census of the significance of giant mesopelagic protists to the marine carbon and silicon cycles, *Nature Communications* 2024, 15(1), 3341. <https://doi.org/10.1038/s41467-024-47651-4>.

Leistenschneider C, Wu F, Primpke S, Gerdtts G & Burkhardt-Holm P, Unveiling high concentrations of small microplastics (11–500 μm) in surface water samples from the southern Weddell Sea off Antarctica. *Science of The Total Environment* 2024, 927, 172124, <https://doi.org/10.1016/j.scitotenv.2024.172124>.

Purser A, Hehemann L, Boehringer L, Tippenhauer S, Wege M, Bornemann H, Pineda-Metz SEA, Flintrop CM, Koch F, Hellmer HH, Burkhardt-Holm P, Janout M, Werner E, Glemser B, Balaguer J, Rogge A, Holtappels M & Wenzhoefer F, A vast icefish breeding colony discovered in the Antarctic, *Current Biology* 2022, 32(4), 842-850.e844, <https://doi.org/10.1016/j.cub.2021.12.022>.

Purser A, Hehemann L, Boehringer L, Werner E, Pineda-Metz SEA, Vignes L, Nordhausen A, Holtappels M & Wenzhoefer F, The COSMUS expedition: seafloor images and acoustic bathymetric data from the PS124 expedition to the southern Weddell Sea, Antarctica. *Earth Syst. Sci. Data* 2022, 14(8), 3635–3648. <https://doi.org/10.5194/essd-14-3635-2022>.

Rogge A, Oziel L, Grotheer H, Campos van Caspel M, Steiger N, Henkel S, Flintrop C, Nissen C, Janout M, Hauck J, Holtappels M, Carbon budget of the southern Weddell Sea shelf reveals its role as efficient and currently stable CO₂ sink, in prep.

Steiger N, Sallée JB, Darelius E, Janout M & Østerhus S, Observed Pathways and Interannual Variability of the Warm Inflow Onto the Continental Shelf in the Southern Weddell Sea, *Journal of Geophysical Research: Oceans* 2014, 129(11), e2023JC020700, <https://doi.org/10.1029/2023JC020700>.

Schall E, (2021) Spatio-temporal patterns in humpback whale (*Megaptera novaeangliae*) acoustic presence and acoustic behavior in the Atlantic sector of the Southern Oceans, 2021, Phd thesis.

Wietz M, Rogge A, Klaas C, Janout M & Holtappels M, Sea ice driven bloom scenarios shape POC export and biological diversity in the central Weddell Sea , in prep.

List of conference presentations

2021 | **Preliminary impressions of an autumn sea ice bloom in the eastern Weddell Sea 2021**, BEPSII/ECVice 2021 online meeting

2022 | **Icefish spawning aggregation in the southern Weddell Sea**, CCAMLR Working Group on Ecosystem, Monitoring and Management, Kiel, Germany

2022 | **Antarctica's meltwater – a global player?**, Topic 2 Invited Talk Geomar, Kiel, Germany

2022 | **Impact of phytoplankton composition on aggregate formation and carbon export in the southern Weddell Sea**, Gordon Research Conference “Ocean Biogeochemistry”, Castelldefels, Spain

2022 | **Impact of phytoplankton composition on carbon export in the southern Weddell Sea**, Gordon Research Conference “Ocean Biogeochemistry”, Castelldefels, Spain

2022 | **Light, iron and manganese availability: major drivers of Southern Ocean phytoplankton ecology and productivity**, Gordon Research Conference “Ocean Biogeochemistry”, Castelldefels, Spain

2022 | **Iron and Manganese: major drivers of Southern Ocean phytoplankton ecology and productivity**, Topic 6 Symposium, Bremerhaven, Germany

2023 | **Dense water driven lateral injection into the Weddell Sea basin: Latest results from the project Southern Weddell-C-Pump**, Topic 6 Symposium, Bremerhaven, Germany

2023 | **Carbon transformation and injection with dense waters from the southern shelf into the Weddell Sea basin**, Science week, Bremerhaven, Germany

2023 | **The importance of sea-ice derived cryogenic minerals on ballasting marine algae aggregates in the polar oceans**, International Symposium on Sea Ice, Bremerhaven, Germany

2023 | **Autumn sea ice bloom in the eastern Weddell Sea with potential implications for the ocean-ice-atmosphere system**, Gordon Research Conference “Polar Marine Science”, Ventura, USA

2024 | **Microbial Seasonality in the Arctic and Antarctic Oceans: From Gene to Ecosystem**, Gordon Research Conference “Marine Microbes”, Les Diablerets, Switzerland

2024 | **The combined effect of light, iron and manganese availability on Southern Ocean phytoplankton growth and productivity**, Ocean Science Meeting, New Orleans, USA

2024 | **Low light conditions promote FeMn co-limitation of the key diatom *Fragilariopsis* in two Weddell Sea phytoplankton assemblages**, Regional Working Group Workshop “Weddell Sea Dronning Maud Land, online meeting

2024 | **Southern Ocean phytoplankton – Key drivers of CO₂ uptake**, EUREKA symposium, Würzburg, Germany

Data

Master track of POLARSTERN cruise PS124 in 1 sec resolution:
<https://doi.org/10.1594/PANGAEA.933462>

Master tracks in different resolutions:
<https://doi.org/10.1594/PANGAEA.933473>

Multibeam bathymetry raw data:
<https://doi.org/10.1594/PANGAEA.948683>

Multibeam bathymetry processed data:
<https://doi.org/10.1594/PANGAEA.954628>

Sediment echosounder raw data:
<https://doi.org/10.1594/PANGAEA.974477>

Radiosonde measurements:
<https://doi.org/10.1594/PANGAEA.935190>

Meteorological observations:
<https://doi.org/10.1594/PANGAEA.935270>

Ceilometer CL51 raw data:

<https://doi.org/10.1594/PANGAEA.935274>

Continuous thermosalinograph oceanography:

<https://doi.org/10.1594/PANGAEA.938767>

Physical oceanography based on ship CTD:

<https://doi.org/10.1594/PANGAEA.957614>

Physical oceanography measured on water bottle samples:

<https://doi.org/10.1594/PANGAEA.961780>

Calibrated chlorophyll concentrations for ship CTD profiles:

<https://doi.org/10.1594/PANGAEA.963564>

Calibrated chlorophyll concentration for water bottle samplings:

<https://doi.org/10.1594/PANGAEA.963561>

Trace gas for glacial meltwater and water ages:

<https://doi.org/10.1594/PANGAEA.971321>

Raw data from moorings AWI252-3, AWI253-3 and AWI254-3 in Filchner Trough:

<https://doi.org/10.1594/PANGAEA.944430>

Raw Data from mooring AWI244-6 in the Weddell Sea:

<https://doi.org/10.1594/PANGAEA.971936>

Data from mooring M3 on the upper continental slope, east of Filchner Trough:

<https://doi.org/10.1594/PANGAEA.962043>

Data from mooring M6 on the upper continental slope, east of Filchner Trough:

<https://doi.org/10.1594/PANGAEA.964715>

Ocean Floor Observation and Bathymetry System (OFOBS) Seafloor images:

<https://doi.org/10.1594/PANGAEA.936205>

OFOBS Images of ice fish nest arrays:

<https://doi.org/10.1594/PANGAEA.932827>

OFOBS Seafloor ice berg circumnavigation images:

<https://doi.org/10.1594/PANGAEA.936223>

OFOBS Seafloor bathymetric maps from side scan:

<https://doi.org/10.1594/PANGAEA.939087>

OFOBS Side scan sonar and swath bathymetry:

<https://doi.org/10.1594/PANGAEA.939322>

OFOBS Forward facing acoustic camera seafloor sonar:

<https://doi.org/10.1594/PANGAEA.939341>

Time series seafloor image data from SWS-WetCam1 mooring:

<https://doi.org/10.1594/PANGAEA.979804>

Phytoplankton experiments with light, iron and manganese supply:

<https://doi.org/10.1594/PANGAEA.967722>

Phytoplankton experiments with iron and manganese supply:

<https://doi.org/10.1594/PANGAEA.957278>

Immobilisation dose rates for Weddell seals:

<https://doi.org/10.1594/PANGAEA.932497>

Weddell Seal tracking and diving data:

<https://doi.org/10.1594/PANGAEA.942997>

Whale sightings:

<https://doi.org/10.1594/PANGAEA.939124>

Snow stratigraphy measurements at ice stations:

<https://doi.org/10.1594/PANGAEA.945857>

Snow-Micro-Pen (SMP) force profiles:

<https://doi.org/10.1594/PANGAEA.945875>

Snow thickness measurements at ice stations:

<https://doi.org/10.1594/PANGAEA.946177>

Snow and sea ice drift from buoy 2021S112:

<https://doi.org/10.1594/PANGAEA.964917>

Snow and sea ice drift from buoy 2021S113:

<https://doi.org/10.1594/PANGAEA.964920>

Snow and sea ice drift from buoy 2021S114:

<https://doi.org/10.1594/PANGAEA.964921>

Snow and sea ice drift from buoy 2021S115:

<https://doi.org/10.1594/PANGAEA.964922>

Temperature and heating-induced temperature difference of SIMBA-thermistor chain:
<https://doi.pangaea.de/10.1594/PANGAEA.967935> (dataset in review)

Snow and Ice Mass Balance Array (SIMBA) buoy 2021T86:
<https://doi.org/10.1594/PANGAEA.973349>

Cruise report

PS124: https://doi.org/10.48433/BzPM_0755_2021

PS129

The expedition PS129 of RV Polarstern in 2022 in the Atlantic sector of the Southern Ocean

Authors

Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany

M. Hoppema, O. Boebel, H. Flores, F. Mark, B. Koch, J. Tebben, M. Graeve, K.-U. Ludwigowski, J. Allerholt, A.K. Beyer, C. Engicht, C. Held, M.E. Kaufmann, S. Kempf, N. Koschnik, P.J. Llanillo del Rio, M. Pallentin, O. Pinner, A. Purser, I. Roca Torrecilla, H. Schröder, S. Spiesecke, S. Tippenhauer, M. Vorkamp

University of Rostock | Rostock, Germany

H. Link, C. Gebhardt, M. Powilleit

Universidad de Las Palmas de Gran Canaria | Las Palmas de Gran Canaria, Spain

M. González-Dávila, J.M. Santana Casiano

British Antarctic Survey | Cambridge, United Kingdom

E.P. Abrahamsen, D. Barnes, J. Wilkinson

Rijksuniversiteit Groningen | Groningen, the Netherlands

M.G. Bach

University of Nottingham | Nottingham, United Kingdom

L. Chakrabarti

University of Basel | Basel, Switzerland

G. Erni Cassola, K. Leuenberger

Koninklijk Nederlands Instituut voor Onderzoek der Zee | Texel, the Netherlands

B. Feij

National Oceanic and Atmospheric Administration | La Jolla, U.S.A.

C. Jones

Wageningen Marine Research | Den Helder, the Netherlands

S. Kühn, A. Meijboom

University College London | London, United Kingdom

R. Mallett

Universita Degli Studi Di Padova | Padova, Italy

C. Papetti

Vlaams Instituut voor de Zee | Oostende, Belgium

C. Parcerisas Serrahima

Institut Royal des Sciences Naturelles de Belgique | Brussels, Belgium

A. Van de Putte

M. van Dorssen Metaalbewerking | Texel, the Netherlands

M. van Dorssen

The expedition PS129 of RV *Polarstern* provided contributions to scientific projects encompassing physical oceanography, marine biology and marine chemistry, with the aim to investigate the water masses of the Weddell Sea and adjacent oceanic regions, and the ecological and chemical cycles within the regions. This expedition is a continuation of the long-term work in the framework of Hybrid Antarctic Float Observation System (HAFOS). The time series has existed since the 1980-90s for hydrography, nutrients, oxygen and carbon system. An additional, substantial part of this expedition was concerned with the program Eastern Weddell Sea Observation System (EWOS). In addition, the project Chemical controls on Organic Matter Aggregation (COMA) has investigated the transitions between dissolved, colloidal and particulate organic matter in the ocean. *Polarstern* started from Cape Town on 3 March 2022. Sailing south until reaching the Antarctic continent near Neumayer station, she turned west to the Kapp Norvegia region where the multi-day EWOS program was carried out. Thereafter, the ship crossed the Weddell Sea completing the SR4 line for hydrography and moorings, nutrients, oxygen and carbon. During crossing, two southward excursions were made for additional mooring work. Finally, we crossed Drake Passage to the call at Punta Arenas/Chile on 28 April 2022.

Extending our long-term ocean-bottom temperature time series by another three years, position 61°S 0°E was occupied for the 16th time, having 30 years of observations (1992–2022). Temperature shows a near-linear continuation of the warming of the Weddell Sea Bottom Water (WSBW). Below a depth of 5300 m, the temperature increased from -0.8435°C (1992) to -0.7759°C, which is an increase of 0.0225°C per decade. Towards the tip of the Antarctic Peninsula, sampling at enhanced horizontal resolution was done, once again repeating a section being occupied there since 1988, i. e., 34 years of coverage. The surface layer exhibits Antarctic Surface Water offshore and Shelf Water onshore. Warm Deep Water

(WDW) was centered around 1000 m depth. The thin sliver of cold water ($< -0.7^{\circ}\text{C}$) at the continental slope is indicative of newly formed WSBW flowing northward along the slope. L-ADCP measurements along the SR4 section confirmed the known flow patterns. The measurements near the Peninsula reveal that the velocity fronts near the 2000 m isobath are barotropic while those farther offshore exhibit a strong baroclinicity.

Recordings of moored acoustic recorders (SonoVault) exhibited enhanced energy in the fin and blue whale bands and frequent broadband events, probably related to storms and cryophonic sound. In all sampled sites, the pack-ice related *pinniped* species followed a similar temporal pattern, with crabeater seals being acoustically conspicuous at the sites from September to December, leopard seals from October/November to January and Ross seals from the end of December to January. Only on one location, crabeater seal calls were heard from July on. Single vocalizations and/or choruses of Antarctic blue whales, fin whales and Antarctic minke whales were very common at almost all positions. Sperm whale clicks were observed, but not very frequently. Orca clicks and whistles were heard, however, their frequency was very low.

COMA aimed to track the proportion of dissolved organic matter (DOM) that is exported by deep-water formation. We sampled water for the concentration of dissolved organic carbon (DOC) and sample extracts with ultrahigh-resolution mass spectrometry (HRMS) to develop proxies that are suitable to track DOM downwelling. The chemical characterization via HRMS may help to elucidate the chemical features that are involved in aggregation. So far, we analyzed almost all samples for DOC concentration and characterized 60 selected extracts that were sampled in the water column near the Antarctic Peninsula.

As to EWOS, two Agassiz trawls between stranded icebergs contained a high volume of biological material – several juvenile notothenioid fish, high diversity of invertebrates and masses of loose, dead bottom material comprised of bryozoans, encrusting algae and sponge spicules, documenting the destruction of the benthic communities in this shallow area by iceberg scouring. Fish traps and long lines were deployed, with only few species caught. A multiple opening Rectangular Midwater Trawl was used to investigate deeper-dwelling macrofauna key species of the pelagic food web. The species composition was dominated by krill at 50% of the stations, whereas at other stations gelatinous zooplankton (jellyfish, chaetognaths and salps) dominated. The omnivorous krill *Thysanoessa macrura* occurred throughout the sampling area. In oceanic waters, Antarctic krill *Euphausia superba* was abundant. Salps were abundant in the Weddell Sea. The two species, *Salpa thompsoni* and *Ihleia racovitzai*, occurred in different depth strata. Particularly high numbers were found at a station in the inner Weddell Sea, where a massive ice-algae bloom stained the surface water and pancake ice in yellowish-green colors. Under-ice and surface-dwelling fauna were sampled:

Antarctic krill dominated the catch on the prime meridian. At a station in the inner Weddell Sea, the under-ice species community was numerically dominated by pteropods (*Limacina helicina*), followed by ice amphipods and Antarctic krill.

The distribution of acoustic backscatter of zooplankton and fish in the water column down to 1000 m depth was recorded with the ship's Simrad EK80 echosounder. Over 14 TB of hydroacoustic data were collected. A deep-scattering layer was observed between 200 and 700 m depth. In the southeastern Weddell Sea, this scattering layer remained at mesopelagic depth and did not follow the bottom topography onto the shelf. The vertical distribution of scatterers followed a diel pattern with deeper distribution at day and many scatterers reaching the surface at night.

While passing through the newly forming marginal sea-ice zone, we crossed a wide band of pancake ice with an intense greenish-yellow coloration, indicating extremely high ice-algae biomass. The algal biomass appeared to be associated with the pancakes and brash ice in-between, whereas the water appeared to contain only low concentrations of biomass. In pancake ice, ice cores for pigment analysis, dimethylsulfoniopropionate (DMSP) measurements, DNA, POC/trophic biomarkers, nutrient concentration, production measurements and salinity profiles were sampled. In the water column, samples were taken for in the surface layer for pigment analysis (HPLC), nutrients, PAM-fluorometry, particulate organic carbon (POC)/trophic biomarkers, as well as dimethylsulfide and DMSP.

Around the Polar Front, hourglass dolphins, long-finned pilot whales, humpback whales and southern right whales were sighted. Occasionally, large groups of snow petrels (>300) were found resting in the vicinity of icebergs. During helicopter surveys, Weddell seals were found close to the shelf resting on remnant thicker ice floes. Crabeater and leopard seals as well as Adélie and emperor penguins were found in a band with thicker ice floes north of Cape Norvegia. Within the sea-ice area of the Weddell Sea, the densities of top predators were low compared to earlier summer expeditions. Penguins, snow petrels, Antarctic petrels and Antarctic minke whales were found close to the ice edges. As the ice closed up, most marine mammals and birds, except penguins, were absent. During one helicopter survey, four rarely observed Arnoux's beaked whales were observed. More to the west, two other groups were encountered in small leads within the sea ice. Closer to the peninsula, with decreasing water depth, large groups of Adélie penguins and seals were encountered, together with small groups of Orcas within the sea ice.

Approximately an hour of video was collected from each dive with the ROV. We will identify biota present as far as possible including the density of each type. Under ice-shelf, iceberg and sea-ice biota will be compared and results analyzed to examine what these exploratory dives can tell us about the nature and fate of under-shelf life.

Benthic processes are a missing component to estimate the overall role of benthos in potential carbon sequestration. In sediment cores, fluxes of oxygen were determined and solutes from incubation chambers together with microbial to macrofaunal assemblages were sampled. Experiments and sampling of particle and solute flux tracers will provide the mechanistic link of benthic biota activity and organic matter remineralization. Benthic processes are quantified as the short-term oxygen consumption, nutrient- and solute tracer fluxes, as well as particle reworking activity at and below the sediment-water interface caused by macro- and meiobenthic communities. Data from sediment communities are currently being evaluated in the BEnToolsMaPs of the “Blue Ocean Biodiversity” call. Bioturbation (fauna-induced particle and fluid transport in the sediment) was determined for the first time, where a fauna-indicated bioturbation depth of 4–7 cm was measured.

Seafloor habitats and their associated epibenthic megafauna were investigated with the Ocean Floor Observation and Bathymetry System (OFOBS), a towed device capable of concurrently collecting acoustic as well as video and still image data from the seafloor. At different sites, observations were made, such as: cup corals and shrimp, with occasional octopi, fish and echinoids; a bryzoa- and sponge-rich seafloor community, and several areas of seafloor which had been scoured by icebergs; occasional fish nest forms behind dropstones, and various fish; a mix of trawl scoured seafloor and occasional islands of fauna undisturbed by the nets, no extensive recolonization of trawled areas by megafauna were observed.

New insights emerge from the EWOS work: (1) the region of the EWOS work may constitute an important nursery area for the ecologically important forage fish *Pleuragramma antarctica* and other Antarctic fishes, including those breeding in nests, (2) the autumn bloom in the young ice of the Weddell Sea may lead to the incorporation of large amounts of biomass in the sea ice, which may further sustain the ecosystem during winter and into the next spring, (3) the underside of ice shelves and icebergs constitutes a potentially important but hitherto neglected habitat. First data from the EWOS study were used to develop the project “Weddell Sea Observatory of Biodiversity and Ecosystem Change” (WOBEC; wobec.aq) which was funded in the Biodiversa+ program of the European Union. In the framework of WOBEC, a follow-up expedition (PS152) was successfully submitted, taking place in 2025/2026.

Scientific Output

List of Publications

Llanillo PJ, Kanzow T, Janout MA & Rohardt G, The deep-water plume in the northwestern Weddell Sea, Antarctica: Mean state, seasonal cycle and interannual variability influenced by climate modes, *Journal of Geophysical Research: Oceans* 2023, 128, e2022JC019375, <https://doi.org/10.1029/2022JC019375>.

Leuenberger K, Erni-Cassola G, Leistenschneider C & Burkhardt-Holm P, Microplastic ingestion in five demersal, bathydemersal and bathypelagic fish species from the eastern Weddell Sea, Antarctica, *Science of The Total Environment* 2024, 946, 174320, <https://doi.org/10.1016/j.scitotenv.2024.174320>.

Feij B, Kühn S, Meijboom A, van Franeker JA, Bornemann H, Kelly N & Schaafsma FL, Distribution of Arnoux's beaked whales (*Berardius arnuxii*), *Marine Mammal Science* 2024, 41, e13158, <https://doi.org/10.1111/mms.13158>.

Pinner O, Pollmann F, Janout M, Voet G & Kanzow T, Internal-wave-induced dissipation rates in the Weddell Sea Bottom Water gravity current, *Ocean Science* 2025, 21, 701-726, <https://doi.org/10.5194/os-21-701-2025>.

Carrillo-Barragán P, Erni Cassola G & Burkhardt-Holm P, Microbial colonisation of polyethylene in offshore marine environments: Insights from the Southern and South Atlantic Oceans, *Science of The Total Environment* 2025, 996, 180189, <https://doi.org/10.1016/j.scitotenv.2025.180189>.

Willatt R, Mallett R, Stroeve J, Wilkinson J, Nandan V & Newman T, Ku- & Ka-band polarimetric radar waveforms and snow depth estimation over multi-year Antarctic sea ice in the Weddell Sea, *Geophysical Research Letters* 2025, 52, e2024GL112870, <https://doi.org/10.1029/2024GL112870>.

Wöhle S, Paker L, Burkhardt E, van Opzeeland I & Schall E, Shifts in acoustic signature of Southern Hemisphere fin whales: Declining peak frequency of high-frequency components, *JASA Express Letters* 2025, 5, 101201, <https://doi.org/10.1121/10.0039500>.

Hancock C, Speer K, Janout M & Boebel O, Under ice-shelf eddy at the Stancomb-Wills Ice Tongue, *Journal of Geophysical Research: Oceans* 2025, 130, e2024JC021393, <https://doi.org/10.1029/2024JC021393>.

List of conference presentations

2022 | **The Eastern Weddell Sea Observation System (EWOS): A multinational initiative that provides coordinated and systematic observations of the Antarctic marine ecosystem** WG-EMM, CCAMLR, Hobart, Australia.

2023 | **DMSP production, primary productivity and community composition in new year sea ice in the Weddell Sea** International Symposium on Sea Ice across Spatial and Temporal Scales, Bremerhaven, Germany.

2025 | **Establishing a Weddell Sea observatory: the WOBECE initiative for long-term biodiversity and ecosystem monitoring** WG-EMM, CCAMLR, Hobart, Australia.

2025 | **Establishing a Weddell Sea observatory: Advances through the WOBECE initiative for long-term biodiversity and ecosystem monitoring** CCAMLR Scientific Committee, CCAMLR, Hobart, Australia

Data

Master tracks in different resolutions:

<https://doi.pangaea.de/10.1594/PANGAEA.947251>

Master track:

<https://doi.pangaea.de/10.1594/PANGAEA.947248>

Raw physical oceanography and ocean current velocity data from mooring AWI207-11:

<https://doi.pangaea.de/10.1594/PANGAEA.971922>

Raw physical oceanography and ocean current velocity data from mooring AWI229-14:

<https://doi.pangaea.de/10.1594/PANGAEA.971907>

Raw physical oceanography and ocean current velocity data from mooring AWI208-9:

<https://doi.pangaea.de/10.1594/PANGAEA.971915>

Raw physical oceanography data from mooring AWI231-13:

<https://doi.pangaea.de/10.1594/PANGAEA.971909>

Raw physical oceanography data from mooring AWI227-15:

<https://doi.pangaea.de/10.1594/PANGAEA.971901>

Raw physical oceanography data from mooring AWI248-3:
<https://doi.pangaea.de/10.1594/PANGAEA.971913>

Raw physical oceanography and ocean current velocity data from mooring AWI251-3:
<https://doi.pangaea.de/10.1594/PANGAEA.971933>

Raw physical oceanography data from mooring AWI245-5:
<https://doi.pangaea.de/10.1594/PANGAEA.971914>

Passive acoustic monitoring data by recorder SV1006 at mooring AWI227-15:
<https://doi.pangaea.de/10.1594/PANGAEA.982238>

Passive acoustic monitoring data by recorder SV1002 at mooring AWI251-3:
<https://doi.pangaea.de/10.1594/PANGAEA.983651>

Passive acoustic monitoring data by recorder SV1012 at mooring AWI248-3:
<https://doi.pangaea.de/10.1594/PANGAEA.973123>

Passive acoustic monitoring data by recorder SV1056 at mooring AWI231-13:
<https://doi.pangaea.de/10.1594/PANGAEA.986812>

Passive acoustic monitoring data by recorder AU0085 at mooring AWI251-3:
<https://doi.pangaea.de/10.1594/PANGAEA.982321>

Passive acoustic monitoring data by recorder SV1014 at mooring AWI245-5:
<https://doi.pangaea.de/10.1594/PANGAEA.973771>

Biogeochemical variables (inorganic nutrients):
<https://doi.pangaea.de/10.1594/PANGAEA.962774>

Continuous thermosalinograph oceanography:
<https://doi.pangaea.de/10.1594/PANGAEA.955769>

Physical oceanography from APEX floats 9223 and 9224:
<https://doi.org/10.17882/104966>

Radiosonde measurements:
<https://doi.pangaea.de/10.1594/PANGAEA.974541>

Whale sightings:
<https://doi.org/10.1594/PANGAEA.972595>

Video footage of Arnoux's beaked whales (*Berardius arnuxii*):
<https://doi.pangaea.de/10.1594/PANGAEA.957764>

Cruise Report

PS129: https://doi.org/10.57738/BzPM_0776_2023

PS131

ATlantic WAter pathways to the ICE in the Nansen Basin and Fram Strait: Results from the ATWAICE expedition

Authors

Alfred-Wegener-Institute Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany

T. Kanzow, W.-J. von Appen, C. Haas, V. Schlindwein, K. Metfies, S. Torres-Valdes

University of Bremen | Bremen, Germany

C. Havermans, G. Spreen

Leibniz Institute for Tropospheric Research | Leipzig, Germany

A. Babu Suja

University of Cologne | Cologne, Germany

K. Ebell

Summary

The expedition PS131 ATlantic WAter pathways to the ICE in the Nansen Basin and Fram Strait (ATWAICE) addressed important goals defined in the programme POF IV of the research field “Earth and Environment” of the Helmholtz Association with a focus on Topic 2: “Ocean and Cryosphere in Climate” and Topic 6: “Marine and Polar Life”. Our work was divided into four major aims. The prime objective 1 was a multidisciplinary process study of ocean-sea ice interaction and the couplings to biogeochemistry, biology and the atmosphere in the marginal ice zone (MIZ) north of Svalbard. Objective 2 of ATWAICE represents the continuation of the mooring-based long-term monitoring of the exchange flows in Fram Strait (as part of AWI’s interdisciplinary FRAM infrastructure in the Arctic Ocean) – realizing the strong need for long-term year-round monitoring programmes at key ocean sites in order to quantify anthropogenically-introduced changes. Objective 3 targeted ocean impacts on major marine-terminating glaciers in (North)east Greenland. Objective 4 constituted a lithospheric study in the Aurora vent field at the western end of Gakkel Ridge. The latter was the primary objective of ALOIS expedition (PS137)

which we supported by deploying instrumentation. The expedition track is shown in Figure 1.

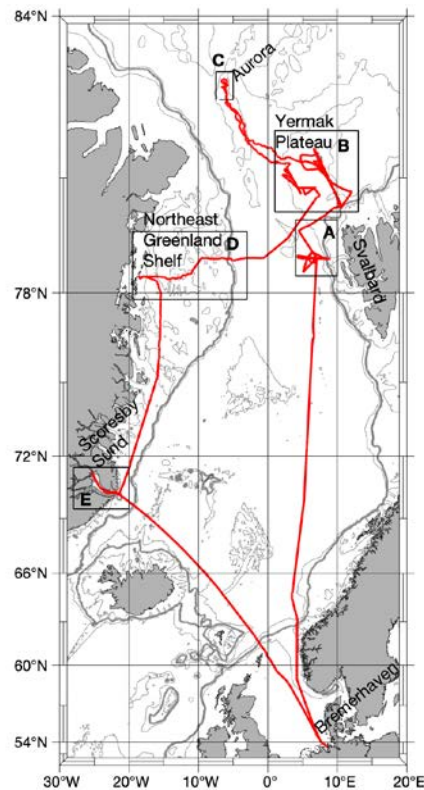


Figure 1: Track of expedition PS131. The boxes A, B, C, D and E mark the different work areas of Eastern Fram Strait, the marginal ice zone, Aurora vent field, Northeast Greenland and Scoresby Sund, respectively.

Scientific Results

1. Ocean-sea ice interaction and the couplings to biogeochemistry, biology and the atmosphere in the marginal ice zone (MIZ)

The work done during PS131 constituted the instrumentation of three ice floes in the MIZ on Yermak Plateau with ocean and sea ice sensors, as well as interdisciplinary sampling activities during three visits on each of the three floes during the expedition. Also, ship-based measurements were conducted and moorings were deployed, all of which have been recovered during subsequent cruises (PS137, PS143.2, PS150).

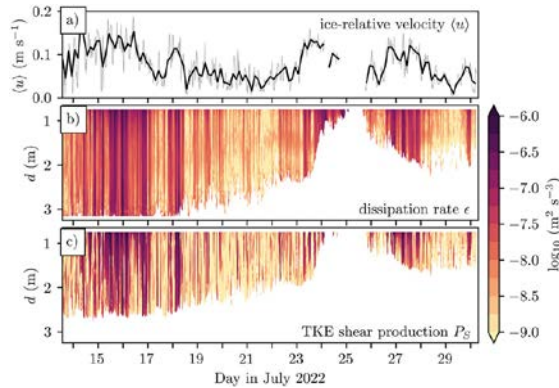


Figure 2: Temporal variability of observed under-ice turbulence: (a) along-stream component of the ice-relative velocity at 0.75-m depth, (b) dissipation rate, and (c) shear production. The vertical axes in (b) and (c) show the distance d from the ice-ocean interface. Source: Reifenberg et al. (2025).

The ice floe sensor time series allowed us to investigate the turbulent processes occurring beneath drifting sea ice, focusing on how turbulent kinetic energy (TKE) is generated and dissipated in the oceanic boundary layer influenced by meltwater. Reifenberg et al. (2025) used direct turbulence measurements to analyze the interplay between ice melt, stratification, and turbulent mixing (Figure 2). The study highlights how meltwater from the ice creates a fresh, buoyant layer near the surface, which can suppress vertical mixing and alter the balance between TKE production (driven by shear and buoyancy) and dissipation. The authors find that the presence of meltwater significantly modifies the structure of the boundary layer, with implications for heat and momentum exchange between the ice, ocean, and atmosphere. The study contributes to understanding of how seasonal ice melt influences ocean mixing and energy budgets, which are crucial for climate modeling and ecosystem studies.

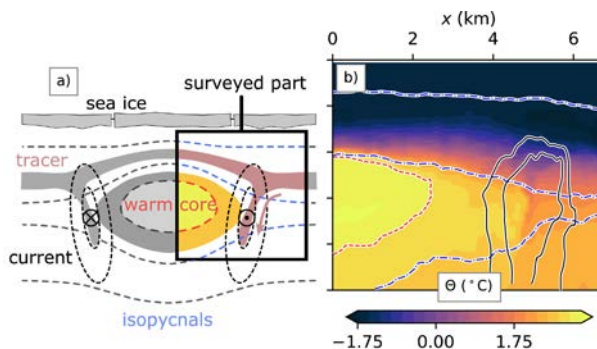


Figure 3: High-resolution survey of a warm anticyclone. (a) Sketch of the authors' interpretation of the observations. Depth-distance fields of (b) temperature. The 3°C isotherm (red), 0.20 and 0.25 m s⁻¹ isotachs (black), and 27.3, 27.8, 27.865 kg m⁻³ isopycnals (blue lines) are indicated. Source: Reifenberg and Fer (2025).

In a second study, Reifenberg and Fer (2025) explored how turbulent mixing in the upper Arctic Ocean near Yermak Plateau is enhanced by the interaction between tidally-forced internal waves and mesoscale shear flows (Figure 3). The authors use high-resolution turbulence measurements from a 24h ice station as well as mooring data to show that tidal currents, as they propagate through regions of strong mesoscale shear (such as eddies or fronts), can generate intense internal wave activity. These interactions lead to elevated levels of turbulent kinetic energy dissipation, which in turn drives vertical mixing in the ocean's upper layers. The study emphasizes the importance of this process for redistributing heat, nutrients, and momentum, particularly in the Arctic where stratification and ice cover can limit mixing.

During PS131 we also assessed the biogeochemical and biological environment of the marginal ice zone in relation to sea ice and ocean stratification. Different machine learning approaches are used and evaluated to extract melt pond information from helicopter-borne thermal infrared imagery (Reill et al., under review), and sea ice and ocean temperatures were continuously monitored by ship-based underway radiometer measurements (Rückert et al., 2025). The towed ocean profiler Triaxus was deployed multiple times and in particular one 150-km long oceanographic section was collected reaching from the open ocean across the MIZ into 100% sea ice covered waters. The achieved horizontal resolution is <800m and this represents the first such towed data set in substantial sea ice cover. The data show that insolation-driven surface melt is generally higher in the inner MIZ than close to the ice back (von Appen, et al., in prep). Towards the outer MIZ, the increasing presence of near-surface Atlantic Water further enhances the melting especially of smaller ice-floes. As a consequence, the substantial meltwater input and the resulting near surface stratification intensify towards the outer MIZ and even affect the upper meters of the open ocean that surrounds the MIZ. Our data show that due to the alleviated light limitation, phytoplankton cells can form extensive blooms in thin layers and consume dissolved nutrients in the water column from the surface downward.

Von Friesen et al. (2025) analysed nitrogen fixation rates across different stages of sea ice retreat in the Central Arctic Ocean and the MIZ. Along two transects through the MIZ (from PS131), these rates fluctuated daily and with ice conditions, from undetectable levels up to $5.3 \pm 3.65 \text{ nmol N L}^{-1} \text{ d}^{-1}$, particularly during an ice-edge phytoplankton bloom. In the Central Arctic Ocean (data obtained from a separate expedition), nitrogen fixation rates were positively linked to primary production, with values ranging from 0.4 ± 0.1 to $2.5 \pm 0.87 \text{ nmol N L}^{-1} \text{ d}^{-1}$. The findings demonstrate active nitrogen fixation in sea ice-covered Arctic waters. As sea ice in the Arctic Ocean continues to decline due to climate change, nitrogen is becoming a key factor in regulating primary productivity, with nitrogen fixation playing a crucial role in this context.

A multi-marker metabarcoding approach was used to investigate the eukaryotic diversity in the upper water column under the ice, at ice floes representing different ice regimes. A range of sympagic and pelagic metazoan taxa were identified, several of which known for the region. However, a substantial amount of uncharacterized (unassigned) diversity was revealed and sea-ice physics clearly shaped community structure. Hence, the under-ice communities of the Marginal Ice Zone are unique and therefore susceptible to climate-induced changes in ice properties (Murray et al., 2025).

Observations of Atmospheric Aerosol Particles were conducted. Throughout the cruise, the observed total number concentration of aerosol particles varied from 10 to 2000 cm⁻³. The highest values of refractory black carbon (rBC) and light scattering were observed during the initial phase of the campaign (up to 70°N), where the air mass trajectories were contributed almost equally by the continental and marine influence. During the campaign, the ship encountered a warm air mass intrusion in the northern section of the marginal ice zone, and we observed significant enhancement in the aerosol concentrations

2. Mooring-based long-term monitoring of the exchange flows in Fram Strait

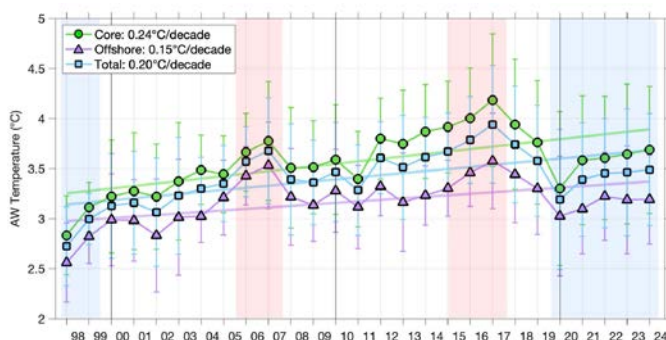


Figure 4: Timeseries of annually averaged AW temperatures for the WSC core, the offshore branch, and the combined WSC. Linear trends for each branch are plotted as lines. Shading marks warm and cold AW temperature anomalies. Source: McPherson et al. (under review).

The West Spitsbergen Current (WSC) brings warm and saline Atlantic Water (AW) northwards from the Nordic Seas, and constitutes the main source of oceanic heat and salt to the Arctic Ocean. The year-round inflow of AW in the WSC has been monitored by AWI's mooring array, providing hydrographic and current data from 1997–2024. During PS131 we serviced the mooring array successfully. The data recovered are part of a study (McPherson et al., under review; Figure 4) revealing a long-term AW warming trend of 0.2°C/decade is observed, resulting in a total warming of the WSC of over 0.5°C over the 27 years. Multi-annual warm and cool AW temperature anomalies are shown to propagate through Fram Strait, typically lasting 2 to 4 years.

3. Ocean impacts on major marine-terminating glaciers in (North)east Greenland.

The AW temperature anomalies in the WSC are advected downstream, with roughly half of the waters recirculating in Fram Strait and moving along / onto the shelf of East Greenland. Direct observations from the 79North Glacier calving front (obtained before PS131) reveal decreasing AW temperatures below the ice tongue from 2018 to 2021, leading to reduced ocean heat transport. This is linked to a concurrent decrease in basal melt and thinning rates at the grounding line. Using the WSC temperature time series recovered by PS131, McPherson et al (2024) were able to trace the AW cooling at the glacier upstream to the Nordic Seas. They concluded the origin of the AW cooling is due to atmospheric blocking patterns that strengthen the cold air advection from the Arctic resulting both in a slowdown of the AW circulation and increased ocean heat loss to the atmosphere. Blocking has driven major ocean cooling events over the last 50 years and will remain crucial in affecting Northeast Greenland's glaciers.

During PS131 we also recovered moorings from another major glacial fjord system in east Greenland, namely Scoresby Sund, between summer 2018 and summer 2022. Combining the observations with an ocean general circulation model suggests that the pronounced interannual variability of the warm Atlantic Water AW is related to advection by the East Greenland Current from Fram Strait along the continental slope of Greenland. We can show (Kanzow et al., in prep) that the interannual AW signature also penetrates far into Scoresby Sund to the transition to Nordvestfjord (Figure 5). The subsurface inflow of AW into Nordvestfjord shows distinct maxima in summertime, most pronounced in 2018 and 2019 but less in 2021 and missing in 2020, suggesting that the inflow is partly driven by a meltwater plume at the head of the fjord. Overall, the observations reveal a superposition of both remote and regional open-ocean influence as well as fjord dynamics to drive ocean-glacier interaction in Scoresby Sund.

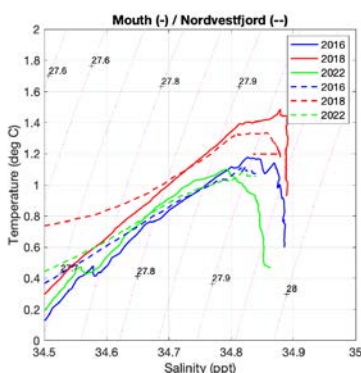


Figure 5: Temperature-salinity diagrams obtained near the fjord mouth of Scoresby Sund (solid lines) and at the transition to Nordvestfjord (dashed lines) between 2016 and 2022 (PS131 contributed the 2022 profiles).

4. Aurora vent field

PS131 supported the subsequent cruise PS137 with the deployment of sensors at the Aurora hydrothermal vent field on Gakkel Ridge. For one year, the microearthquake activity around the vent field was monitored along with its hydrothermal plume which out to be laterally confined but rising to 900 m above seafloor (Walter et al. 2025).

References

McPherson RA, Wekerle C, Kanzow T, Ionita M, Heukamp FO, Zeising O & Humbert, A, Atmospheric blocking slows ocean-driven melting of Greenland's largest glacier tongue, *Science* 2024, 385(6715), 1360–1366.

Murray A, Ramondenc S, Reifenberg SF, Jucker M, Neudert M, McPherson R, et al., Eukaryotic biodiversity of sub-ice water in the marginal ice zone of the European arctic: A multi-marker eDNA metabarcoding survey, *Science of the Total Environment* 2025, 968, 178840, <https://doi.org/10.1016/j.scitotenv.2025.178840>.

Reifenberg SF & Fer I, Turbulent mixing in the upper Arctic Ocean energized by interactions of tidally-forced waves with mesoscale shear, *Geophysical Research Letters* 2025, 52, e2025GL117468, <https://doi.org/10.1029/2025GL117468>.

Reifenberg SF, Fer I, Kanzow T, von Appen W-J, Hoppmann M, Krumpfen T, et al., Turbulence observations below drifting sea ice: TKE production and dissipation in the meltwater-influenced boundary layer, *Journal of Physical Oceanography* 2025, 55(4), 451–470, <https://doi.org/10.1175/JPO-D-24-0102.1>.

Rückert JE, Walbröl A, Risse N, Krobot P, Haseneder-Lind R, Mech M, Ebell K & Spreen G, Microwave sea ice and ocean brightness temperature and emissivity between 22 and 243 GHz from ship-based radiometers, *Annals of Glaciology* 2025,66, e8, 1–16, <https://doi.org/10.1017/aog.2025.1>.

von Friesen LW, Farnelid H, von Appen W-J, et al., Nitrogen fixation under declining Arctic sea ice, *Comm. Earth & Environment* 2025, <https://doi.org/10.1038/s43247-025-02782-4>.

Walter M, Türke A, Diehl A, German CR, Mertens C, Mette J, Monien P, Prause S, Sültenfuß J, Bach W, Schlindwein V & Boetius A, Properties and dispersal of a hydrothermal plume in a weakly stratified under-ice environment, *Geochemistry Geophysics Geosystems* 2025, 26, e2024GC012016, doi:10.1029/2024GC012016.

Scientific Output

List of Publications

a) accepted/published

McPherson RA, Wekerle C, Kanzow T, Ionita M, Heukamp FO, Zeising O & Humbert A, Atmospheric blocking slows ocean-driven melting of Greenland's largest glacier tongue, *Science* 2024, 385(6715), 1360–1366.

Murray A, Ramondenc S, Reifenberg SF, Jucker M, Neudert M, McPherson R, et al., Eukaryotic biodiversity of sub-ice water in the marginal ice zone of the European arctic: A multi-marker eDNA metabarcoding survey, *Science of the Total Environment* 2025, 968, 178840. <https://doi.org/10.1016/j.scitotenv.2025.178840>.

Reifenberg SF & Fer I, Turbulent mixing in the upper Arctic Ocean energized by interactions of tidally-forced waves with mesoscale shear, *Geophysical Research Letters* 2025, 52, e2025GL117468, <https://doi.org/10.1029/2025GL117468>.

Reifenberg SF, Fer I, Kanzow T, von Appen W-J, Hoppmann M, Krumpen T, et al., Turbulence observations below drifting sea ice: TKE production and dissipation in the meltwater-influenced boundary layer, *Journal of Physical Oceanography* 2025, 55(4), 451–470, <https://doi.org/10.1175/JPO-D-24-0102.1>.

Rückert JE, Walbröl A, Risse N, Krobot P, Haseneder-Lind R, Mech M, Ebell K & Spreen G, Microwave sea ice and ocean brightness temperature and emissivity between 22 and 243 GHz from ship-based radiometers, *Annals of Glaciology* 2025,66, e8, 1–16, <https://doi.org/10.1017/aog.2025.1>.

von Friesen LW, Farnelid H, von Appen, W-J, et al., Nitrogen fixation under declining Arctic sea ice, *Comm. Earth & Environment* 2025, <https://doi.org/10.1038/s43247-025-02782-4>.

Walter M, Türke A, Diehl A, German CR, Mertens C, Mette J, Monien P, Prause S, Sültenfuß J, Bach W, Schlindwein V & Boetius A, Properties and dispersal of a hydrothermal plume in a weakly stratified under-ice environment, *Geochemistry Geophysics Geosystems* 2025, 26, e2024GC012016, doi:10.1029/2024GC012016.

b) under review

Bracher A, Xi H, von Appen W-J, Mehdipour E, Metfies K, McPherson R, Zeising M & Nöthig E-M, Resolving the interannual variability of phytoplankton community composition in Fram Strait using ship-based high-frequency spectrophotometric

measurements from 2015 to 2024, Submitted to Deep-Sea Research (under review).

Dolinkiewicz M, Cornils A, Hildebrandt N, McPherson R, von Appen W-J & Niehoff B, Zooplankton dynamics in the Fram Strait from 2011 to 2023: Linking abundance, biodiversity, and environmental conditions, Submitted to Deep-Sea Research (under review).

McPherson R, von Appen W-J, de Steur L, Kanzow T, Beszczynska-Möller A & Renner A, Decades of Change: Warming Trends and Hydrographic Variability of Atlantic Water as observed in the West Spitsbergen Current (1997–2024), Submitted to Deep-Sea Research (under review).

McPherson R, Lochthofen N, Reifenberg S, von Appen W-J & Xi H, Year-round vertically resolved observations of upper ocean hydrography and biogeochemistry in the Atlantic Water inflow north of Svalbard Submitted to Deep-Sea Research (under review).

Reil M, Spreen G, Huntemann M, Buth L & Wilson DG, (2025, submitted), Deep Learning for the Detection of Melt Ponds on Sea Ice From Airborne Infrared Images, Submitted to Environmental Data Science (under review).

List of conference presentations

2023 | **Observations of Summer Ice Melt and Ice-Ocean Boundary Layer Heat Fluxes in the Marginal Ice Zone North of Fram Strait** IGS Symposium on Sea Ice, Bremerhaven, Germany

2023 | **Nitrogen fixation under declining Arctic sea ice.** ASLO Aquatic Sciences meeting, Palma de Mallorca, Spain

2024 | **Formation of extremely high phytoplankton concentrations in the meltwater stratified marginal ice zone.** AGU/ASLO Ocean Sciences Meeting, New Orleans, LA, USA

2024 | **Hydrographic variability and submarine glacial melt in Scoresby Sund: Open-Ocean and glacier controls.** ASOF, Halifax, Canada

2024 | **Turbulent Processes in the Under-Ice Boundary Layer in the Marginal Ice Zone During Melt Season** Ocean Mixing Conference (GRC), South Hadley (MA), USA

2024 | **Machine Learning for the Detection of Arctic Melt Ponds from Infrared Imagery** International Conference on Learning Representations (ICLR) Workshop: Tackling Climate Change with Machine Learning, Vienna, Austria

2025 | **Overview of Atmospheric Aerosol Observations during the ATWAICE Expedition in the Central Arctic** EGU General Assembly, Vienna, Austria.

2025 | **Eukaryotic biodiversity in sub-ice water column across the Marginal Ice Zone of the European Arctic: A multi-marker eDNA metabarcoding survey.** Australian and New Zealand environmental DNA conference, Wellington, New Zealand

Data

There are 84 data sets associated with PS131 in the Pangaea archive. They are in the fields of physical oceanography, sea ice physics, biology, biogeochemistry, atmospheric sciences and geophysics. The list of data sets can be found under the link: <https://www.pangaea.de/?q=PS131>

Cruise Report

PS131: https://doi.org/10.57738/BzPM_0770_2023

PS132

North south atlantic training 2022 (oceancapx | nosoat)

Authors

Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany

K. Wiltshire, E.-M. Brodte, A. Dummermuth, B. Dorschel, K. Dorschel, Maïté Guignard, Y. Schulz Tenberge, P. Schwarzbach, V. Sidorenko, D. Sidorenko

Institute for Chemistry and Biology of the Marine Environment | Oldenburg, Germany

S. Lennartz, H. Simon

Max Planck Institute for Marine Microbiology | Bremen, Germany

R. Amann, L. Rößler

National University of Ireland | Galway, Ireland

P. Croot

The Hebrew University of Jerusalem | Jerusalem, Israel

Y. Avidani

University of East Anglia | Norwich, Great Britain

A Baker

The expedition PS132 of *Polarstern* started on 30.08.2022 in Bremerhaven and ended on 29.09.2022 in Cape Town. The expedition was one of a series of international shipboard training in cooperation with the NIPPON-Foundation and the Partnership for Observation of the Global Ocean (POGO) to educate young scientist and gather long-time data on fixed stations in the Atlantic Ocean. The group of 13 scholars from 13 nations has been trained in oceanographic techniques, microbiology and ocean knowledge during this training. The scholars learned observation methods, sampling techniques and data collection, as well as processing and dealing with the accompanying data. The main water masses between the North Sea and the Atlantic were characterized in terms of their hydrographic features down to a depth of approx. 500 m and more.

The expedition covered an enormous geographic range on the transit through temperate and sub-tropical regions. Water components such as phytoplankton, Coloured Dissolved Organic Matter (CDOM), and non-algal particles affect the optical variability of the upper layer of the ocean. The absorption properties of these components are thus used to assess changes in phytoplankton composition and for the evaluation of primary production models based on remote sensing data. The absorption coefficients of total particulate matter ($a_p(\lambda)$) in seawater samples collected at ten stations were measured. The latitudinal and vertical variability of $a_p(434)$, $a_p(670)$, B/R ratio, and normalized particulate absorption spectral shape at each station was analyzed and the normalized $a_p(\lambda)$ curves were classified into three levels: Surface (10 m), Deep Chlorophyll Maximum (DCM) and the layer below the observed differences between the absorption coefficient of particulate matter and its spectral shape confirm that $a_p(\lambda)$ variability depends on physicochemical conditions of the medium (e. g. radiant energy, nutrient concentration, and temperature).

During the expedition 15 xBT measurements were done and analyzed. The variation of the mixed layer depth is from 20 to 50 m in the Northern Hemisphere and up to 120 m in the Southern Hemisphere, which is agreed with the mean September mixed layer depth according to World Ocean Atlas and FESOM output. As expected, we observed a relatively deep thermocline at the edge of the subtropical gyre as a result of Ekman pumping and a relatively shallow thermocline at the Equator as a result of Equator upwelling (Figure 1). Modelling results show the same patterns. However, the position of the core of the Mediterranean Outflow water masses is shifted in FESOM results compared to the observations. It is situated between 600 and 1,000 m depth in the modelling simulations and between 800 and 1,200 in the observations. Also, the modelling output provides a relatively narrower core compared to the observations. One of the reasons of such a discrepancy is the relatively coarse vertical resolution at the mentioned vertical horizon, other possible reasons should be further studied.

The ADCP were collected and analysed during 11 CTD stations. Data show the development of the Ekman spiral nearly at half of the stations. Additionally, ADCP measurements allow to trace the dominant near-surface current system in the area. As an example, nearby the Canarian Islands the mean vertical profile of the horizontal velocities during CTD station time presents the Ekman's spiral at first 30–50 m and below there is clear footprint of the Canarian current system. The magnitude of velocities ranges from 0.7 to 0.5 m s⁻¹ along the Ekman spiral, decreasing from the top to the bottom. Below 50 m, a nearly homogenous velocity profile in a sense of magnitude and direction with a magnitude of about 0.3 m s⁻¹ was recorded.

In order to understand the response of the Eastern Atlantic Ocean, we calculated the ocean heat content (OHC) of five CTD stations of the PS132 transect. We

also computed and compared how much heat the ocean (at these stations) has absorbed spanning up to 37 years (1985–2022). The OHC was calculated as the vertical integral of temperature multiplied by the seawater density and specific heat capacity. With archival data constraints, the stations selected include locations off the Strait of Gibraltar, North of Las Palmas, off the Guinean Coast, at the Equator and off the Angolan coast. Over a short-term range (2008–2022) from surface to maximum depth, the station off the Angolan coast has accumulated the highest heat between 2012 and 2022 by $2,499 \times 10^{10}$ Joules. This can be attributed to the heat source from the Indian Ocean through the Agulhas Leakage (Lee et al., 2011). The second warmest, station off the Strait of Gibraltar, increased by $1,720 \times 10^{10}$ J but it is highly influenced by the Mediterranean Outflow Water (MOW). On a long-term range (1985–2022) over the upper ocean (0–850 m), the stations North of Las Palmas and off Guinean Coast have warmed by about $5,960 \times 10^9$ J. With a special focus on the MOW, we observed a currently cooling water mass with a strong variability over the years studied. A considerable amount of heat stored by the ocean over the years is apparent in the changing temperature profiles, but further studies need to be conducted on the impact of the MOW on the Atlantic Ocean.

In studies on the Bacterioplankton, we used oceanic provinces sensu Longhurst (Longhurst, 2007) to predict patterns related to the trophic level, i. e., green vs. blue waters. The latitudinal North-South Atlantic transect covered by PS132 included eleven CTDs from the following Longhurst provinces: NADR (North Atlantic Drift province), NAST (North Atlantic Subtropical), CNRY (Canary Current/Upwelling), ETRA (Eastern Tropical Atlantic), SATL (South Atlantic gyre province), BENG (Benguela Current/Upwelling). We hypothesized that the green/blue water pattern along PS132 would be reflected in more/fewer bacteria (TCC), respectively. Green waters were expected to have higher relative abundances of typical heterotrophic groups such as Flavobacteriia and Gammaproteobacteria compared to blue water. SAR11 abundances should be higher in blue waters under oligotrophic conditions (Brüwer et al., 2024).

Aerosols during the expedition show patterns; Orange/brown coloration was observed on the $> 1 \mu\text{m}$ fractions of aerosol samples 7 and 8, which is indicative of the presence of Saharan dust in these samples. This is typically associated with higher level atmospheric transport of dust, which then enters the surface atmosphere through gravitational settling. For much of the period 7–13 September, the surface wind direction coincided with the ship's course, so that the aerosol collectors were disabled by the wind sector controller. Samples 11–16 contained noticeable amounts of soot, with the highest amounts apparent in sample 14. The most likely source of this material is biomass burning in southern Africa, as southern hemisphere spring is the peak burning season in this region. Samples will be analyzed for tracers of biomass burning (e. g., excess potassium) in order to test this hypothesis. Faint orange/brown coloration was also noticeable on the

larger size fractions of samples 17 & 18. Surface winds were southeasterly during this period and the Namib Desert may be a potential source for this material.

During PS132, the bathymetric surveys were conducted with the hull-mounted multibeam echosounder (MBES) Teledyne Reson HYDROSWEEP DS3. a track length of 5,758 nm (10,663 km) was surveyed by the swath bathymetry.

Detecting carbonyl sulfide and carbon disulfide emissions and their role of marine emissions in the atmospheric budget of carbonyl sulfide led to analyzing the isotopic fingerprint of COS and CS₂ in seawater and the marine boundary layer provides information on its spatiotemporal variability. Our measurements constitute the first open-ocean measurements of the isotopic sulfur ratio in COS and its precursor CS₂. Concentrations of COS and CO in surface seawater showed distinct diurnal cycles as expected, with considerable day-to-day variations (Figure 2).

In addition, the scholars learned how to translate knowledge in practice on board e. g., by feeding the Instagram account of the NF-POGO Centre of Excellence for Observational Oceanography. A second example is the miniboat project in the frame of Educational Passages. Pupils from Ireland, Spain, South Africa and Germany assembled little boats equipped with GPS and temperature sensors which have been deployed from *Polarstern* by scholars. The deployment of the miniboats was presented by scholars to the pupils (Brodte et al., 2025). Experiences from the cruise and awareness on the ocean and climate change could be transported directly to the class rooms.

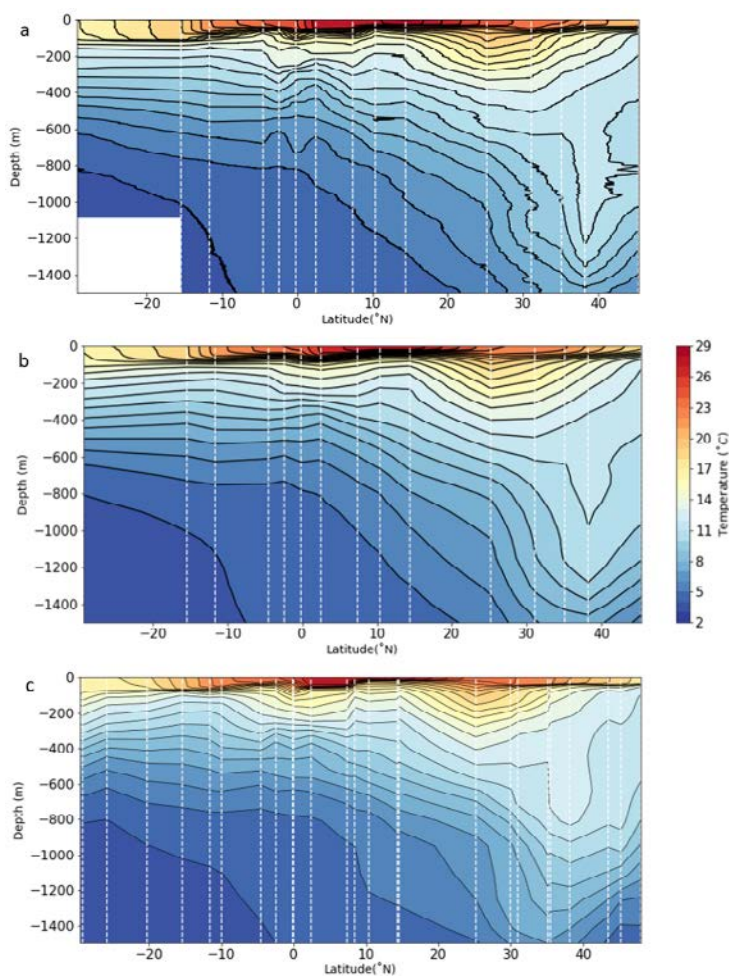


Figure 1: Water temperature profiles (a) measured using xBT probes along the cruise transect, (b) mean for September along the cruise transect obtained from reanalysis, in particular, from World Ocean Atlas 2018, (c) mean simulated by FESOM on NG5 mesh.

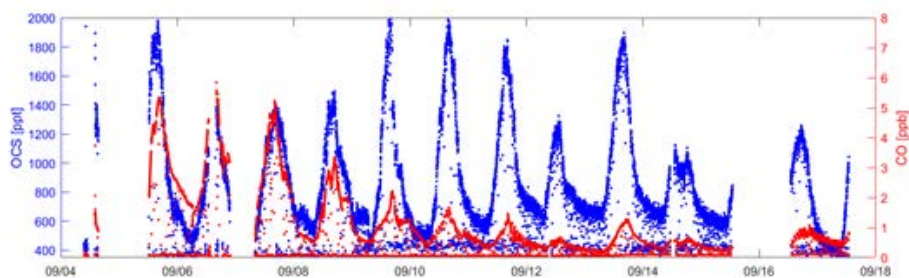


Figure 2: Raw data of continuous measurements of OCS and CO in the marine boundary layer and equilibrated air in the equilibrator supplied with surface seawater.

References

Brodte E-M, et al., The Polarstern Atlantic Transect as a concept for shipboard training on ocean science, ICES Journal of Marine Science 2025, <https://doi.org/10.1093/icesjms/fsaf165>.

Brüwer JD, Sidhu C, Zhao Y, et al., Globally occurring pelagiphage infections create ribosome-deprived cells, Nat Commun 2024, 15, 3715, doi: 10.1038/s41467-024-48172-w.

Lee SK, Park W, van Sebille E, Baringer MO, Wang C, Enfield DB, Yeager SG & Kirtman BP, What caused the significant increase in Atlantic Ocean heat content since the mid-20th century?, Geophys. Res. Lett. 2011, 38:L17607, <https://doi.org/10.1029/2011GL048856>.

Longhurst AR, Ecological geography of the sea (2nd edition), Academic Press 2007, San Diego, USA.

Scientific Output

List of Publications

Brodte, et al., The Polarstern Atlantic Transect as a concept for shipboard training on ocean science, ICES Journal of Marine Science 2025, <https://doi.org/10.1093/icesjms/fsaf165>.

Brüwer JD, Sidhu C, Zhao Y, et al., Globally occurring pelagiphage infections create ribosome-deprived cells, Nat Commun 2024, 15, 3715, doi: 10.1038/s41467-024-48172-w.

Krug L, Beckman F, Rees A, Dummermuth A, Stymiest C, Brodte EM, Wiltshire K, Croot P & Seeyave S, All Aboard! Providing Shipboard Technical Skills While Building Capacity in Ocean Observations, Oceanography 2025, 38 (1), pp. 20–25, doi: 10.5670/oceanog.2025.123.

Wiltshire KH & Dummermuth A, The Expedition PS132 of the Research Vessel POLARSTERN to the Atlantic Ocean in 2022 / H. Bornemann and S. Amir Sawadkuhi (editors) , Berichte zur Polar- und Meeresforschung = Reports on polar and marine research, Bremerhaven, Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung 2023, 771 , 46 p, doi: 10.57738/BzPM_0771_2023.

List of conference presentations

2022 | **NOSOAT**, 1st @SeaNetwork meeting, Cape Town, South Africa.

2023 | **NOSOAT Programme – Polarstern Atlantic Transit Training**, Germany^{2nd}
@SEANET Meeting, online.

2023 | **Fair solutions in Engineering for sustainable oceans, Special panel: Fair solutions in Engineering for sustainable oceans**, Thursday 8th June, Oceans 5.–8.6.2023, Limerick, Ireland.

Data

Master tracks in different resolutions of POLARSTERN cruise PS132, Bremerhaven – Cape Town, 2022-08-30–2022-09-29:
<https://doi.org/10.1594/PANGAEA.952489>

Master track of POLARSTERN cruise PS132 in 1 sec resolution:
<https://doi.org/10.1594/PANGAEA.952488>

Physical oceanography (CTD):
<https://doi.org/10.1594/PANGAEA.958949>

Physical oceanography (Thermosalinograph):
<https://doi.org/10.1594/PANGAEA.964271>

Microbiology (Microscopy data):
<https://doi.org/10.17617/3.3ZLOAT>

Microbiology (Metagenomes) are publicly available from the European Nucleotide Archive (ENA) with the accession code PRJEB52999
<https://www.ebi.ac.uk/ena/browser/view/PRJEB52999>

Microbiology (databases): GTDB release 202 [<https://data.gtdb.ecogenomic.org/>], RefSeq (online via NCBI website) as of October 22nd, 2023 [<https://ftp.ncbi.nlm.nih.gov/refseq/release/viral>], and the nt database of the NCBI blast server as of February 14th, 2023.

Bathymetry (Multibeam raw data):
<https://doi.org/10.1594/PANGAEA.956866>

Bathymetry (Multibeam processed data):
<https://doi.org/10.1594/PANGAEA.954700>

Cruise Report

PS132: https://doi.org/10.57738/BzPM_0771_2023

PS133/1 and PS133/2

“Island Impact” – Understanding the regional impact of islands (South Georgia) on Southern Ocean biogeochemistry and ecosystem function

Authors

**Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research |
Bremerhaven, Germany**
S. Kasten, C. Klaas

Faculty of Geosciences, University of Bremen | Bremen, Germany
S. Kasten

**MARUM – Center for Marine Environmental Sciences, University of Bremen |
Bremen, Germany**
S. Kasten

and Cruise Participants and Partners of Expedition Legs PS133/1 and PS133/2

Objectives

Some of the highest concentrations of phytoplankton in the Southern Ocean occur in proximity and downstream of the archipelago of South Georgia (e. g., Park et al., 2010). These substantial algal blooms require a significant iron (Fe) source for their development. Islands have been shown to be important sources of Fe for the large phytoplankton blooms in open ocean areas of the Southern Ocean. South Georgia is the largest island of the Scotia Arc, situated in the northeastern Scotia Sea. The objective of expedition PS133 with RV POLARSTERN (Legs PS133/1 and PS133/2) performed from October to December 2022 was to understand the sources and pathways of input and transport of Fe and other nutrients (both macronutrients and trace metals) into South Georgia Island shelf waters and further downstream in the Southern Antarctic Circumpolar Current (ACC). For

this purpose, we investigated the main Island-derived (shelf, fjord, on-shore) sources of Fe, nutrients and other trace metals including benthic fluxes from sediments and the impact of injection of these compounds by methane bubble ebullition and groundwater seepage. Seeps, groundwater, meltwater runoff and sediments may all play a role here. A further aspect of our investigations was to assess if and how industrial-scale whaling performed at Grytviken in Cumberland Bay fjord between 1904 and the mid-1960s has impacted and is still affecting geochemical characteristics and biogeochemical processes in the near-shore and deeper fjord sediments – in particular with respect to the cycling of carbon, sulfur, iron and other nutrients. We investigated how these local island-derived and other potential Fe sources contribute to the downstream biogeochemistry and the ecosystem structure in the Atlantic sector of the Southern Ocean, through large-scale and high-resolution surveys extending from the Island shelf into the Georgia Basin and downstream within the Southern ACC. We used an innovative and unprecedented approach that covered the whole source-to-sink continuum ranging from sampling and measurements on-shore and proximal to glaciers via transects along several fjords towards the shelf and into the open ocean – i. e. into the Georgia Basin. This should improve our understanding of physical connectivity and sources and modes of iron supply in the island system and downstream along the ACC (including sub-mesoscale and mesoscale processes), as well as particle dynamics and sources and biogeochemical processes transforming and transporting Fe downstream along the ACC as well as the impact of the different modes of Fe and nutrient supply on productivity, ecosystem characteristics and export through the biological carbon pump.

Leg PS133/1

During leg PS133/1 (Figure 1), the impact of iron and other trace metals on plankton productivity (net and primary production), community composition (from bacteria to macrozooplankton) as well as the suite of processes leading to atmospheric CO₂ uptake and C export at depth were investigated. These studies encompassed the whole water column (surface down to bottom sediments) and were carried out along the flow of the Antarctic Circumpolar Current (10°W to 42°W) with decreasing distance from the main source for trace elements, namely the Island and shelves of South Georgia. Further, at strategic locations, high resolution (mesoscale to submesoscale) oceanographic surveys with the help of towed instruments were carried out to determine the sources and transport mechanisms for nutrients – including iron – and carbon along and across the flow of the Antarctic Circumpolar Current. Finally, the South Sandwich trench was sampled at three different locations as part of an ongoing study of hadal systems.

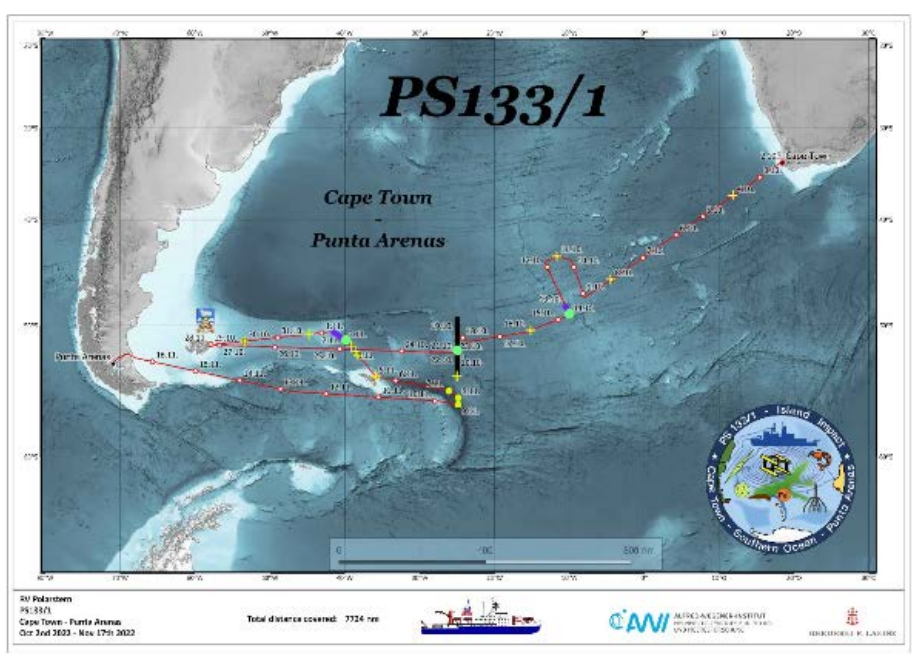


Figure 1: Cruise track of Leg PS133/1.

Leg PS133-2

The main focus of leg PS133-2 (Figure 2) was to assess and investigate the sources as well as the reaction and transport pathways of nutrients – including iron – and carbon in several fjords and shelf areas of the South Georgia archipelago. For this purpose we deployed a broad spectrum of sampling tools from board the RV POLARSTERN – including amongst others a trace-metal clean CTD-Rosette system, in situ pumps, state-of-the-art particle sampling devices (snow catcher, gel traps, etc.), an in situ mass spectrometer for the determination of dissolved methane concentrations in the water column as well as a multiple corer and a gravity corer for the retrieval of undisturbed surface and deeper subsurface sediments. In addition, measurements and sampling with a hand-held CTD, Niskin bottles to collect water samples and a hand-held small gravity corer for the collection of surface sediments were operated from board of Zodiacs in proximity of glacier fronts and in shallow-water coastal areas of the selected fjords. Furthermore, several groups went on-shore to sample different water sources - including surface water runoff, glacial-meltwater streams, meltwater ponds and sites of submarine groundwater discharge. As key sites/fjords for our investigations we chose Cumberland Bay fjord located in eastern South Georgia where intensive industrial-scale whaling took place at Grytviken and King Haakon Bay fjord in the west of the archipelago where no such whaling activities were performed.

First results – amongst others – suggest that benthic fluxes of iron from sediments into the overlying water column significantly vary along the investigated fjords. We found a strong positive correlation between the magnitude of diffusive benthic Fe fluxes and the total organic carbon accumulation rate (MAR_{TOC}), which controls the redox zonation of the surface sediments and also the range and the stable iron isotopic composition ($\delta^{56}Fe_{aq}$) of pore waters (Ebner et al., in review; cf. Scientific Contributions below and separate poster presentation). An ongoing study also suggests that natural organic matter coatings in sediments of fjords of South Georgia fundamentally alter microbe–mineral–organic carbon interactions, and consequently the fate of iron-bound organic carbon (Chen et al., in prep.; cf. *separate poster presentation*). The investigation of the bioavailability of iron from different sources to phytoplankton revealed that aggregation of dissolved organic matter in high chlorophyll waters scavenged dissolved Fe, making it largely unavailable to phytoplankton. In contrast, in low chlorophyll waters, as opposed to Fe from groundwater, Fe from glacial meltwater was bioavailable to phytoplankton and is suggested to increase CO_2 fixation by 80–100 % (Stimpfle et al., in review; cf. *Scientific Contributions below and separate poster presentation*). An investigation of macrobenthic communities in different sedimentary fjord habitats revealed that seafloor sites associated with active methane seepage – a common feature of fjord and trough deposits of South Georgia – supported lower biodiversity and fewer calcifying taxa, indicating potential risks to Antarctic benthic biodiversity under future seep expansion (Anderson et al., in prep.; cf. *separate poster presentation*). Furthermore, we found that sediments adjacent to the former whaling station at Grytviken are visually and geochemically distinct from other South Georgia sites and from high-latitude fjords more broadly. Our findings from Cumberland Bay fjord off Grytviken therefore provide a rare case study of “sedimentary memory” — the ability of benthic environments to retain signatures of past human impact and disturbance on coastal and marine sedimentary ecosystems (Laufer-Meiser et al., in prep.; cf. *separate poster presentation*).

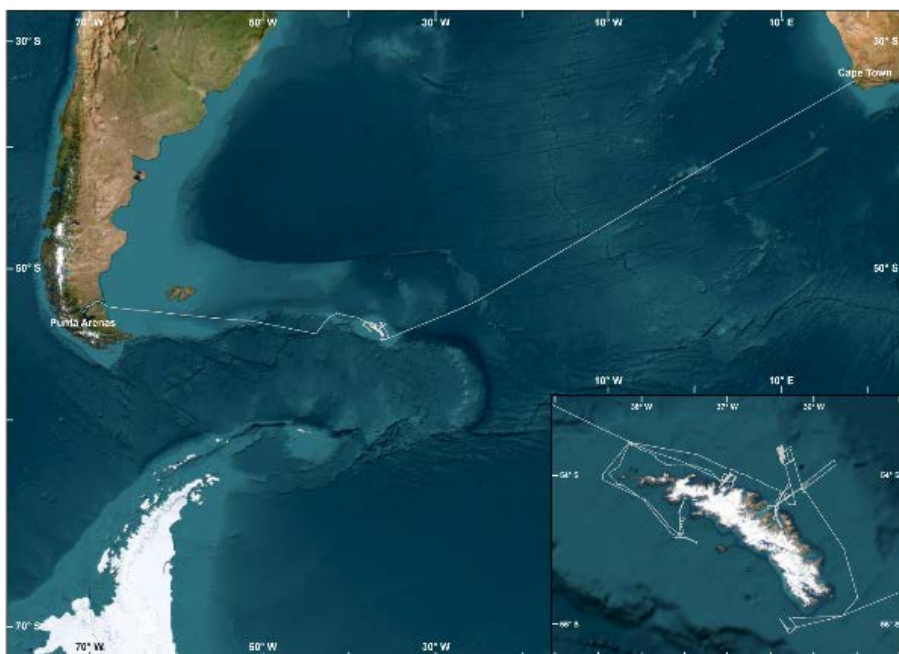


Figure 2: Cruise track of Leg PS133/2.

Scientific Output

List of Publications

Published and accepted

Bracher A, Banks AC, Xi H, David D, et al., Assessment of OLCI absorption coefficients for non-water components across all optical water classes, *Frontiers in Remote Sensing*, accepted, 6, doi:10.3389/frsen.2025.1545664.

Brüwer JD, Sidhu C, Zhao Y, et al., Globally occurring pelagiphage infections create ribosome-deprived cells, *Nature Communications* 2024, 15, 3715, doi: 10.1038/s41467-024-48172-w.

Lešić N-M, Streuff KT, Kuhn G, Kasten S & Bohrmann G, Spatial and Temporal Variability in Holocene Trough-Fill Sediments, King Haakon Trough System, Sub-Antarctic South Georgia, *Quaternary Science Advances* 2024, 13(100156), doi: 10.1016/j.qsa.2023.100156.

Lešić N-M, Late Pleistocene and Holocene sediments around South Georgia: Archives for climate-induced signals in sub-Antarctica since the last glaciation, 2023, PhD dissertation, University of Bremen, Germany, doi:10.26092/elib/2890.

Mole R, von Appen WJ, Becker H, Haumann FA, et al., Wind-driven iron supply by Ekman buoyancy flux enhances phytoplankton bloom in the Antarctic Circumpolar Current. *Journal of Geophysical Research: Oceans* 2025, 130(8), e2025JC022530, doi: 10.1029/2025JC022530.

Pakhomov EA, Mole R, Bahl AA, et al., Early spring population dynamics of *Salpa thompsoni* linked to physical oceanography in the Atlantic sector of the Southern Ocean, *Polar Biology* 2025, 48, 13, doi: /10.1007/s00300-024-03342-w.

Streuff KT, Lešić N-M, Kuhn G, Römer M, et al., Glacial history of the King Haakon Trough System, sub-Antarctic South Georgia, *Quaternary Science Reviews* 2024, 338(108749), doi:10.1016/j.quascirev.2024.108749.

In review

Ebner B, Henkel S, Kraal P, Müller D, et al., Drivers of Benthic Iron Fluxes and the Pore-water Iron Isotopic Signature in Sub-Antarctic Surface Fjord Sediments, in review, *Global Biogeochemical Cycles*.

Stimpfle J, Koch F, Ebner B, Völkner C, et al., Contrasting bioavailability of iron in glacial vs. groundwater to Antarctic phytoplankton: Linking iron uptake to geochemistry, *Communications Earth and Environment*, in review, doi:10.21203/rs.3.rs-7317240/v1.

Submitted

Biester H, Pérez-Rodríguez M, Caezan A, Sindlev MB, et al., Dissolved and particulate monomethylmercury in a highly productive area of the Southern Ocean, *Global Biogeochemical Cycles*, submitted.

Kwan YH, Derycke S, Trouche B, Wenzhöfer F, et al., Trenches Apart, Yet Worm to Worm: Inter- and Intra-Trench Comparisons Reveal Divergent and Convergent Dynamics in Hadal Nematode Biodiversity, *Progress in Oceanography*, submitted.

In preparation

Huang Y, Laghrissi A, Zhao Y, Duan X, et al., A comprehensive approach to microplastic extraction from deep-sea environments: Method validation and application, *Marine Pollution Bulletin*, in prep.

Oskamp L, Pérez-Rodríguez M, Caezan A, Benkhettab Sindlev M, et al., Lead Isotopes in Deep Sea Sediments reveal Alteration of Isotopic Signal in the Water Column at highly productive Sites in the Southern Ocean, in prep.

Bachelor and Master Thesis

Leusch M, Differences in (Bio-)Geochemical Processes, with Emphasis on the Iron Cycle in Sediments of the King Haakon Bay and Cumberland Bay Fjord Systems, South Georgia, 2023, Master Thesis, University of Bremen, Germany

Thorn J, Holozäne Sedimente aus Südgeorgien, Sub-Antarktis - Eigenschaften und Paläorekonstruktion, 2024, BSc Thesis, University of Bremen, Germany.

Schierer T, Benthic iron fluxes and organic matter reactivity in fjord sediments of South Georgia, sub-Antarctica, 2025, Bachelor Thesis, joint AWI-University of Jena Thesis, Germany.

List of conference presentations

2023 | **Expedition PS133-2 “Island Impact” Understanding the regional impact of islands (South Georgia) on Southern Ocean biogeochemistry and ecosystem function** Workshop of the Government of South Georgia and the South Sandwich Islands (GSGSSI) Marine Protected Areas (MPA), British Antarctic Survey, Cambridge, United Kingdom

2023 | **Sediment cores, bathymetry and Parasound data – Illuminating marine depositional archives around sub-Antarctic South Georgia** 46. Arbeitskreis-Treffen Geologie und Geophysik der Polargebiete, Hannover, Germany.

2023 | **Quantifying the bioavailability of nearshore iron sources from South Georgia to phytoplankton**, International Conference for Young Marine Scientists, Oldenburg, Germany.

2023 | **Sources, transport and reaction pathways of iron from terrestrial areas and coastal sediments of South Georgia, Sub- Antarctic** ECORD Summer School, Bremen, Germany

2023 | **Preliminary results of sedimentary stable iron isotope data from South Georgia, Southern Ocean** Goldschmidt, Lyon, France

2023 | **Sources, transport and reaction pathways of iron from terrestrial areas and coastal sediments of South Georgia, Sub- Antarctic** AWI PhD days, Potsdam, Germany

2023 | **Sources, transport and reaction pathways of iron from terrestrial areas and coastal sediments of South Georgia, Sub- Antarctic** MARUM PhD days, Visselhövede, Germany

2023| **From Bubble to Biology** NERC Centre Meeting to Strategic Programme Generation & Delivery Group, Swindon, UK

2024 | **Quantifying the bioavailability of nearshore iron sources from South Georgia to phytoplankton**, Ocean Sciences Meeting, New Orleans, USA.

2024 | **Iron transport and reaction pathways traced by sedimentary stable iron isotopes from South Georgia into the adjacent Southern Ocean** Ocean Sciences Meeting, New Orleans, USA

2024 | **Investigating sedimentary organic carbon reactivity in South Georgia fjord sediments using ^{14}C -analysis and ramped pyrolysis oxidation**, Ocean Sciences Meeting, New Orleans, USA

2024 | **Quantifying the bioavailability of nearshore iron sources from South Georgia to phytoplankton**, AWI Science Week, Bremerhaven, Germany.

2024 | **Elucidating lipid-carbon flux dynamics in the Southern Ocean**, Coordination workshop DFG Priority Program SPP 1158, Cologne, Germany.

2024 | **Early spring *Salpa thompsoni* population dynamics in the Atlantic sector of the Southern Ocean**, 7th International Zooplankton Production Symposium, Hobart, Tasmania, Australia.

2024 | **Late Pleistocene and Holocene sediments around South Georgia: Archives for climate-induced signals in sub-Antarctica since the last glaciation** 29th International Polar Conference (Polartagung), Rauris, Austria.

2024 | **Glacial history of the King Haakon Trough System, sub-Antarctic South Georgia** 29th International Polar Conference (Polartagung), Rauris, Austria.

2024 | **Glacial history of the King Haakon Trough System, sub-Antarctic South Georgia** EGU 2024, Vienna, Austria.

2024 | **Radiocarbon analysis of methane** 4th International Conference on Radiocarbon in the Environment Conference, Lecce, Italy.

2024 | **Elucidating lipid-carbon flux dynamics in the Southern Ocean Part** Coordination workshop DFG Priority Program SPP 1158, Cologne, Germany.

2024 | **Vertical distribution patterns of lipids and lipid-carbon in the western Atlantic sector of the Southern Ocean** Ocean Floor Symposium, Bremen, Germany.

2025 | **The effect of zooplankton community structure on the efficiency of the biological carbon pump in the Southern Ocean**, International Conference for Young Marine Researchers, Bremerhaven, Germany.

2025 | **Iron oxides prevent acetate from microbial degradation in anoxic marine sediments**, Goldschmidt, Prague, Czech Republic.

2025 | **Natural organic matter coating on iron oxide changes its role in carbon preservation in marine sediments**, Ocean Floor Symposium, Bremen, Germany.

2025 | **Drivers of surface distribution of dissolved organic carbon and nitrogen along the northern Antarctic Peninsula and the Atlantic Southern Ocean**, EGU General Assembly 2025, Vienna, Austria.

2025 | **Vertical distribution patterns of lipids and lipid-carbon in the western Atlantic sector of the Southern Ocean**, Ocean Floor Symposium, Bremen, Germany.

2025 | **Elucidating lipid-carbon flux dynamics using next generation sequencing**, Coordination workshop DFG Priority Program SPP 1158, Bremerhaven, Germany.

2025 | **Revealing intra- and inter- trenches biodiversity of hadal meiofauna using molecular approaches**, 17th Deep-Sea Biology Symposium (17DSBS), Hong Kong

2025 | **Diversity and biogeography of archaea in hadal sediments**, Blandine Trouche, 3rd International Conference on Biology, Geology and Environment of Hadal Trenches, Sanya, China.

2025 | **Drivers and iron isotopic signature of benthic Fe fluxes in sub-Antarctic fjord sediments** Scientific Evaluation of the AWI, Bremerhaven, Germany

2025 | **Drivers of benthic iron fluxes and their iron isotopic signature in sub-Antarctic fjord sediments** Goldschmidt Conference, Prague, Czech Republic

2025 | **Fast radiocarbon analysis of methane** 25th Radiocarbon Conference, Krakow, Poland.

2025 | **From Bubbles to Biology: Macrobenthos Abundance, Diversity, and Assemblage Structure at South Georgia's Methane Seeps** 17th Deep-Sea Biology Symposium, Hong Kong, China

2025 | **The abundance, diversity and trophodynamics of the macrobenthos at the South Georgia shelf methane seeps** 16th Gas in Marine Sediments conference, Southampton, UK

Data

Master tracks in different resolutions of POLARSTERN cruise PS133/1, Cape Town – Punta Arenas, 2022-10-02–2022-11-17:
<https://doi.org/10.1594/PANGAEA.957236>

Continuous thermosalinograph oceanography along
RV POLARSTERN cruise track PS133/1:
<https://doi.org/10.1594/PANGAEA.964287>

Raw data of physical oceanography during RV POLARSTERN cruises
PS133/1 and PS133/2. PANGAEA:
<https://doi.org/10.1594/PANGAEA.962314>

Raw data from Triaxus topAWI (towed ocean profiler of the AWI)
during RV POLARSTERN cruise PS133/1:
<https://doi.org/10.1594/PANGAEA.962675>

Raw data from UCTD (Underway CTD) during RV POLARSTERN cruise PS133/1:
<https://doi.org/10.1594/PANGAEA.962681>

PS133.1_6 Dissolved iron profile; surface primary production and iron uptake:
[10.5281/zenodo.15790325](https://doi.org/10.5281/zenodo.15790325)

Absorption coefficients by non-water components at the first eight Ocean Land
Colour Imager bands from a global in-situ collection of open ocean, coastal and
inland surface waters matched to OLCI:
<https://doi.org/10.1594/PANGAEA.983227>

Whale sightings during POLARSTERN cruise PS133/1:
<https://doi.org/10.1594/PANGAEA.963393>

Characteristics of the thaliacean *Salpa thompsoni* population in the Atlantic sector
of the Southern Ocean in early spring:
<https://doi.org/10.1594/PANGAEA.973501>

Nematodes 18S metabarcoding data, European Nucleotide Archive (ENA),
Assession number: PRJEB94967

Master track of POLARSTERN cruise PS133/2 in 1 sec resolution:
<https://doi.org/10.1594/PANGAEA.957579>.

Master tracks in different resolutions of POLARSTERN cruise PS133/2,
Punta Arenas – Cape Town, 2022-11-19–2022-12-19:
<https://doi.org/10.1594/PANGAEA.957577>

Whale sightings during POLARSTERN cruise PS133/2:
<https://doi.org/10.1594/PANGAEA.963426>

Continuous thermosalinograph oceanography along
RV POLARSTERN cruise track PS133/2:
<https://doi.org/10.1594/PANGAEA.964289>

Atmospheric methane concentrations on RV POLARSTERN
cruise PS133/2, in 2022, from Punta Arenas to Cape Town:
<https://doi.org/10.1594/PANGAEA.983729>

Documentation of sediment core PS133/2_35-10:
<https://doi.pangaea.de/10.1594/PANGAEA.969415>

Documentation of sediment core PS133/2_42-11:
<https://doi.pangaea.de/10.1594/PANGAEA.969417>

Documentation of sediment core PS133/2_42-10:
<https://doi.pangaea.de/10.1594/PANGAEA.969416>

Documentation of sediment core PS133/2_23-13:
<https://doi.pangaea.de/10.1594/PANGAEA.969413>

Documentation of sediment core PS133/2_35-9:
<https://doi.pangaea.de/10.1594/PANGAEA.969414>

Dissolved methane concentrations and oxidation rates around South Georgia, in
austral summer 2022:
<https://doi.pangaea.de/10.1594/PANGAEA.984658>

Processed physical properties of sediment core PS133/2_17-13:
<https://doi.org/10.1594/PANGAEA.962127>

Absorption coefficients by phytoplankton at the first eight Ocean Land Colour
Instrument (OLCI) bands from a global in-situ collection of open ocean, coastal
and inland surface waters matched to OLCI:
<https://doi.org/10.1594/PANGAEA.983241>

Absorption coefficients by coloured dissolved organic matter at 443 nm from a global in-situ collection of open ocean, coastal and inland surface waters matched to Ocean Land Colour Instrument:
<https://doi.org/10.1594/PANGAEA.983195>

Absorption coefficients by coloured detrital and dissolved organic matter from a global surface water in-situ collection at the first eight bands of and matched to the Ocean Land Colour Imager (OLCI):
<https://doi.org/10.1594/PANGAEA.983161>

Core photos, PS133-2_42-11:
<https://doi.pangaea.de/10.1594/PANGAEA.969417>
(in review)

Hydroacoustic data, PS133-2:
(in review)

Oxygen profiles, pore-water- and solid phase data of surface sediments retrieved from two fjords in South Georgia, sub-Antarctica: submitted to PANGAEA 29.08.2025 (in review).

Cruise Reports

PS133/1: https://doi.org/10.57738/BzPM_0774_2023
PS133/2: https://doi.org/10.57738/BzPM_0775_2023

PS134

Result overview of RV Polarstern expedition PS134 (WAIS-BELL) to the Bellingshausen Sea of West Antarctica in early 2023

Authors

Alfred Wegener Institute Helmholtz-Centre for Polar and Marine Research | Bremerhaven, Germany

K. Gohl, G. Uenzelmann-Neben, J. Gille-Petzoldt, J. Hamann, J. Klages, L. Cardinahl, S. Dreutter, E. Weigelt, G. Verhaegen, M. Ruiz, B. Dorschel, C. Havermans

British Antarctic Survey | Cambridge, United Kingdom

C.-D. Hillenbrand, R. Larter, J. Kirkham, Z. Welch

University of Bremen, Department of Geosciences | Bremen, Germany

D. Röhnert, C. Brand, C. Spiegel, N. Kaul

Kiel University, Institute of Geosciences | Kiel, Germany

M. Lösing

University of Veterinary Medicine Hannover | Büsum, Germany

J. Baltzer, N. Ramirez Martinez, L. Schick, K. Lucke, U. Siebert

University of Bergen | Bergen, Norway

J. Soto-Ángel

University of Ghent | Ghent, Belgium

M. Troch

University of South Florida | St. Petersburg FL, USA

R. Burkhalter-Castro

Sorbonne University, CNRS | Paris, France

A. Lorenco, K. Himmich, J.-B. Sallée

The Expedition PS134 with the title “West Antarctic Ice Sheet history and processes in the Bellingshausen Sea (WAIS-BELL)” was primarily aimed to assess the development and changes of the ice sheets in West Antarctica in various times of the past. The ice sheets of West Antarctica and the Antarctic Peninsula have been likely subject to highly dynamic activities during periods of climate warming as most of the base of the West Antarctic Ice Sheet is grounded below present sea-level and therefore prone to melting by intruding warm deep water. In addition, most of the Antarctic Peninsula Ice Sheet is exposed to surface warming. Knowing their contribution to sea-level during times when climate conditions were similar as expected of a future warming Earth requires reconstruction of their glacial advance and retreat cycles in relationship to bathymetric, topographic and oceanographic conditions.

The data and samples collected during this expedition help decipher the paleo-environmental processes of the southern Bellingshausen Sea as this region, together with its neighbouring Amundsen Sea sector, exhibits some of the most dramatic ice mass loss developments in modern times. Various hypotheses state that these sectors have always been the most vulnerable locations in Antarctica for early ice sheet retreat in most deglaciation periods. Data produced by using seismic reflection profiling, geothermal heat flow measurements, multibeam bathymetric surveying and sub-bottom profiling serve to study transport, depositional and erosional processes of glacially derived continental shelf sediments and the glacially controlled structural formation of the continental slope. Thermochronological data and analyses of cosmogenic isotopes from rock samples collected from the coastal mainland provide indications on uplift of the Earth's crust as well as the retreat history of the ice sheet since the last glacial maximum. Antarctic jellyfish were sampled as part of a small biological programme to study their diversity, distribution and trophic role in the Southern Ocean. Further, a study on whales was conducted to validate the mitigation methods applied in conjunction with the hydroacoustic and seismic surveys.

The expedition began on 23 December 2022 in Cape Town, South Africa, with the transit across the Southern Atlantic Ocean, the first sampling stations for jellyfish research, and the recovery and deployment of some oceanographic moorings before arriving at Neumayer Station III in western Dronning Maud Land of East Antarctica for resupply. After the transit across Weddell Sea and along a new, storm-avoiding route through the island world of the western Antarctic Peninsula, the main work area in the Bellingshausen Sea was reached. Most of the scientific work projects took place here, before returning to Punta Arenas, Chile, where the expedition ended on 6 March 2023. The extraordinary sea-ice situation with a circum-Antarctic record minimum distribution in this austral summer season led to unexpected ice-free conditions also in the Bellingshausen Sea. Therefore, all research projects of PS134 could be conducted nearly as planned.

More than 3700 km of multi-channel seismic reflection profiles were collected on the continental shelf and slope with excellent data quality. The data show impressive glacial unconformities and changes from aggradational to progradational sequences indicating the shelf growth due to grounded ice sheet expansion (Figure 1). Seismic horizon correlation to drill sites of the Ocean Drilling Program (ODP) Leg 178 on a deep-water sediment drift at the southern Antarctic Peninsula margin allows the establishment of a seismic stratigraphic model for the shelf, the pre-glacial to glacial transition and the reconstruction of ice sheet dynamics since the Miocene. The results can now be compared to pre-glacial conditions, glacial onset, glacial-marine sedimentation processes and reconstruction of the past ice-sheet dynamics of the adjacent Amundsen Sea sector (Gohl et al., 2013; Gohl et al., 2021, Uenzelmann-Neben et al., 2022; Klages et al., 2020; Zundel et al., 2024; Klages et al., 2024).

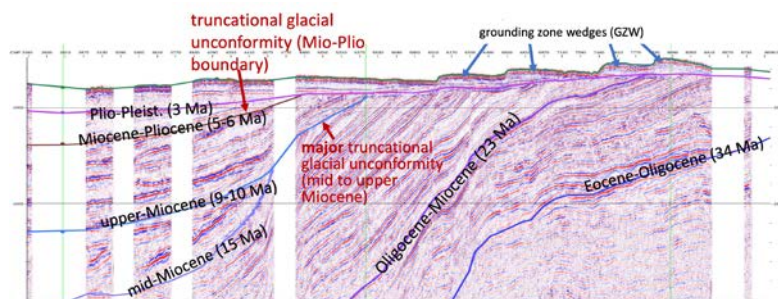


Figure 1: Example of processed seismic data from the Belgica Trough on the Bellingshausen Sea shelf shows major glacial unconformities that indicate initial grounded ice sheet advances.

Detailed bathymetric surveys reveal impressive glacial-morphological formations in several troughs offshore of glaciers of Ronne Entrance, Eltanin Bay and eastern Abbot Ice Shelf. Together with 29 sediment coring stations, sediment echography (Parasound) data and seismic profiles, an integrated analysis of ice sheet variability retreat chronology for the Quaternary, in particular since the Last Glacial Maximum, is currently in progress. This enables a comparison with glacial ice-sheet retreat mechanisms and timing since last glacial maxima between the Bellingshausen Sea and Amundsen Sea embayment shelves (Klages et al., 2014). Numerous geothermal temperature gradient measurements in the shelf sediments resulted in the first geothermal heat flow (GHF) estimates of the region. GHF values are relatively high in Ronne Entrance, but surprisingly low in Eltanin Bay (Brand et al., 2025).

The land geology team collected rock samples from 10 outcrop locations along the coast and some islands. Thermochronological analyses of the material revealed different tectonic blocks with differential exhumation history from the Cretaceous to the Eocene (Simon, 2025).

Meant to be an informal piggy-back project, the observation of meltwater outflows from glaciers in satellite radar imagery combined with ground-truthing visual observations from the ship and helicopter resulted in a novel study on using satellite radar data for the detection of such active meltwater outflows (Hamann et al., 2024).

A total of 16 sampling stations with the discovery of some new species were achieved by the relatively small jellyfish research program. This enables for the first time thorough analyses of the genetic connectivity, diversity and ecology of the different species in different parts of the Southern Ocean (Detsch, 2024; Draudt, 2025).

Although the research program on whales, accompanying the seismic surveys, suffered from a damage of the drone and malfunctioning of the hydroacoustic lander, it documented surprisingly large numbers of marine mammals, in particular whales, by systematic observations from the ship and during helicopter reconnaissance flights.

The collected data and samples on board indicate how dynamic the West Antarctic Ice Sheet has behaved in the Bellingshausen Sea sector in the past. The rich data and sample material enables for the first time a comprehensive analysis and reconstruction of the ice-dynamic processes in climate change-relevant periods of the past in this sector.

References

Brand C, Kaul N, Lösing M & Gohl K, Influence of transient bottom water temperature variations on geothermal heat flow measurements from the Bellingshausen Sea, West Antarctica, and the Baltic Sea, *Journal of Geophysical Research – Oceans* 2025, 130, <https://doi.org/10.1029/2024JC022034>.

Detsch CWG, Genetic connectivity and diversity within the genus *Arctapodema* (Hydrozoa: Trachymedusae) in West Antarctica, BSc thesis 2024, University of Bremen.

Draudt LL, Circumpolar genetic connectivity and ecology of three Antarctic siphonophores (*Diphyes antarctica*, *Heteropyramis crystallina*, *Muggiaea bargmannae*), BSc thesis 2025, University of Applied Sciences, Bremerhaven.

Gohl K, Uenzelmann-Neben G, Gille-Petzoldt J, Hillenbrand CD, Klages J, et al., Evidence for a highly dynamic West Antarctic Ice Sheet during the Pliocene, *Geophysical Research Letters* 2021, 48, <https://doi.org/10.1029/2021GL093103>.

Gohl K, Uenzelmann-Neben G, Larter RD, Hillenbrand CD, Hochmuth K, et al., Seismic stratigraphic record of the Amundsen Sea Embayment shelf from pre-glacial to recent times: Evidence for a dynamic West Antarctic ice sheet, *Marine Geology* 2013, 344, <https://doi.org/10.1016/j.margeo.2013.06.011>.

Hamann JS, Arney T, Kirkham JD, Wachter P & Gohl K, Antarctic ice-shelf meltwater outflows in satellite radar imagery: ground-truthing and basal channel observations, *Journal of Glaciology* 2024, 70, <https://doi.org/10.1017/jog.2024.71>.

Klages JP, Hillenbrand CD, Bohaty SM, Salzmann U, Bickert T, et al., Ice sheet-free West Antarctica during peak early Oligocene glaciation, *Science* 2024, 385, <https://doi.org/10.1126/science.adj3931>.

Klages JP, Kuhn G, Hillenbrand CD, Graham AG, Smith JA, et al., Retreat of the West Antarctic Ice Sheet from the western Amundsen Sea shelf at a pre- or early LGM stage, *Quaternary Science Reviews* 2014, 91, <https://doi.org/10.1016/j.quascirev.2015.02.017>.

Klages JP, Salzmann U, Bickert T, Hillenbrand CD, Gohl K, et al., Temperate rainforests near the South Pole during peak Cretaceous warmth, *Nature* 2020, 580, <https://doi.org/10.1038/s41586-020-2148-5>.

Simon F, Exhumation of the Bellingshausen margin (West Antarctica), BSc thesis 2025, University of Bremen.

Uenzelmann-Neben G, Gohl K, Hochmuth K, Salzmann U, Larter RB, et al., Deep water inflow slowed offshore expansion of the West Antarctic Ice Sheet at the Eocene-Oligocene transition, *Communications Earth & Environment* 2022, 3, <https://doi.org/10.1038/s43247-022-00369-x>.

Zundel M, Spiegel C, Mark C, Millar I, Chew D, et al., A large-scale transcontinental river system crossed West Antarctica during the Eocene, *Science Advances* 2024, 10(23), <https://doi.org/10.1126/sciadv.adn6056>.

Scientific Output

List of Publications

Brand C, Kaul N, Lösing M & Gohl K, Influence of transient bottom water temperature variations on geothermal heat flow measurements from the Bellingshausen Sea, West Antarctica, and the Baltic Sea, *Journal of Geophysical Research – Oceans* 2025, 130, <https://doi.org/10.1029/2024JC022034>.

Hamann JS, Arney T, Kirkham JD, Wachter P & Gohl K, Antarctic ice-shelf meltwater outflows in satellite radar imagery: ground-truthing and basal channel observations, *Journal of Glaciology* 2024, 70, <https://doi.org/10.1017/jog.2024.71>.

List of conference presentations

2023 | **Bipolar jellyfish: evolutionary origin and diversification** 7th International Jellyfish Blooms Symposium, Kerala, India.

2023 | **Diversity, distribution, and connectivity of Antarctic gelatinous zooplankton revealed with state-of-the-art molecular tools** 7th International Jellyfish Blooms Symposium, Kerala, India.

2023 | **Exploring cryptic diversity and speciation in the bipolar species *Ptychogastria polaris*** 10th Workshop of the Hydrozoan Society, Bergen, Norway.

2023 | **Jellyfish in a changing Southern Ocean: an environmental DNA study to reveal their diversity, distribution, connectivity, and ecology** 10th Workshop of the Hydrozoan Society, Bergen, Norway.

2023 | **Evolutionary origin and consequences of diversification by bipolarity: Hydrozoa as a model group** 10th Workshop of the Hydrozoan Society, Bergen, Norway.

2023 | **Gelatinous zooplankton in a changing Southern Ocean: an environmental DNA study to reveal their diversity, distribution, connectivity, and ecology** XIII SCAR Biology Symposium, Christchurch, New Zealand.

2024 | **Towards the completion of NOAH's ark: addressing knowledge gaps in Polar Hydrozoa** Norwegian Symposium in Biosystematics, Oslo, Norway.

2024 | Past dynamics of the West Antarctic Ice Sheet from marine seismic data and drill records: What have we learned? 29th International Polar Conference, Rauris, Austria.

2024 | The tectonomorphic evolution of the Bellingshausen Sea sector of West Antarctica 29th International Polar Conference, Rauris, Austria.

2025 | The Bellingshausen Sea Sector of West Antarctica and its ice-hidden tectonomorphic history Arbeitskreistreffen Geologie und Geophysik der Deutschen Gesellschaft für Polarforschung, Bremerhaven, Germany.

2025 | Miocene to Pliocene/Pleistocene shift in West Antarctic Ice Sheet dynamics in the Bellingshausen Sea and Amundsen Sea sectors European Geosciences Union (EGU) General Assembly, Vienna, Austria.

2025 | Change in geomorphological expression of palaeo-ice stream grounding zone retreat associated with change in bed slope along Belgica Trough, Bellingshausen Sea European Geosciences Union (EGU) General Assembly, Vienna, Austria.

2025 | West Antarctic Ice Sheet dynamics shows major shift from Miocene to Pliocene/Pleistocene in the Bellingshausen Sea and Amundsen Sea sectors International Symposium on Antarctic Earth Sciences (ISAES), Punta Arenas, Chile.

2025 | Hidden under the ice: unravelling the tectonomorphic history of the Bellingshausen Sea Sector, West Antarctica Geo4Göttingen, Göttingen, Germany.

Data

CTD, raw data:

<https://doi.pangaea.de/10.1594/PANGAEA.962405>

Thermosalinograph:

<https://doi.pangaea.de/10.1594/PANGAEA.964292>

Bathymetry, raw data:

<https://doi.org/10.1594/PANGAEA.958669>

Bathymetry, processed data:

<https://doi.org/10.1594/PANGAEA.961243>

Parasound:

<https://doi.pangaea.de/10.1594/PANGAEA.974479>

Geothermal temperatures:

<https://doi.pangaea.de/10.1594/PANGAEA.984027>

Geothermal heat flow (GHF):

<https://doi.pangaea.de/10.1594/PANGAEA.984026>

Thermal conductivity for GHF:

<https://doi.pangaea.de/10.1594/PANGAEA.984029>

Whale sightings:

<https://doi.pangaea.de/10.1594/PANGAEA.964868>

Jellyfish: Barcoding of Life Data System (BOLD), project SOJEL “Southern Ocean Jellyfish”

Jellyfish: Barcoding of Life Data System (BOLD), project SOCON “Southern Ocean gelatinous zooplankton connectivity”

Cruise Report

PS134: https://doi.org/10.57738/BzPM_0777_2023

PS135/1 and PS135/2

Atlantic transit as a scientific opportunity for interdisciplinary ocean and atmosphere research and WASCAL student training

Authors

Alfred Wegener Institute for Polar and Marine Research | Bremerhaven, Germany

Y. Schulze Tenberge

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

B. Fiedler

Helmholtz Centre Hereon | Geesthacht, Germany

Z. Xie

Max Planck Institute for Chemistry | Mainz, Germany

S. Kinne

Expedition PS135 of RV Polarstern (Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung 2017) took place from 9 March to 11 April 2023, a full Atlantic transit from Punta Arenas, Chile, to Bremerhaven, Germany, with a stopover in Mindelo, Cabo Verde. The cruise was split in two legs, PS135/1 and PS135/2. During PS135/1 the focus was on interdisciplinary research specifically bathymetric mapping, atmospheric observations, and chemical contaminant monitoring. The second leg, PS135/2, focused on a dedicated academic training program (WASCAL Floating University) offering hands-on oceanographic experience to West African M.Sc. students while the interdisciplinary research continued. Both legs contributed to long-term environmental data collection and capacity developing across ocean and climate sciences.

Bathymetry

Throughout expedition PS135, continuously bathymetric data were collected with the ship's hull-mounted multibeam echosounder (MBES) system Hydrosweep DS3 with the aim to extend existing data coverage and to fill data gaps along the trans-Atlantic route from Punta Arenas to Bremerhaven. Accurate seabed topography information is essential for interpreting marine processes, such as sediment transport, geological structures, and ocean circulation dynamics. The collected data serve the interdisciplinary need for spatial information for use in habitat modeling, oceanographic station planning, and geohazard assessments, among other uses.

For the calibration of bathymetric data, 7 sound velocity profiles (SVPs) were collected using a Valeport MIDAS Sound Velocity Probe. These profiles allowed for the correction of changes of sound speed in the water column thus reducing refraction-related errors in swath coverage and improving data quality. The SVPs were combined/extended with data from the World Ocean Atlas 2018 (Locarnini et al., 2019; Zweng et al., 2019).

During PS135 approximately 141,830 km² of bathymetric data of mostly uncharted seafloor were collected along 16,636 km of ship track, covering all depths from the deep-sea to continental shelf regions.

As part of the post-cruise workflow, collected data were processed, cleaned, and submitted for publication in accordance with the FAIR principles (Wilkinson et al., 2016) to PANGAEA (Felden et al., 2023). Furthermore, the data were provided to international bathymetric initiatives, such as the General Bathymetric Chart of the Oceans (GEBCO), the Nippon Foundation – GEBCO Seabed 2030 project and EmodNET. The data were incorporated into the latest GEBCO_2025 Grid (GEBCO Bathymetric Compilation Group, 2025). This contribution underlines the importance of routine en-route collection of bathymetric data.

Atmospheric and Oceanic Transport of Emerging Organic Contaminants in the Atlantic Ocean

The large-scale distribution of neutral poly- and perfluoroalkyl substances (PFASs) in the marine atmosphere across the Atlantic Ocean was investigated during the Polarstern cruise PS135 during both legs. Total concentrations of 14 PFASs (Σ PFASs) in air ranged from 14 to 64 pg m⁻³, with an average of 22 pg m⁻³. Fluorotelomer alcohols (FTOHs) dominated the atmospheric burden, accounting for 82.8 ± 6.0% of Σ PFASs. Concentrations were slightly higher in the North Atlantic than in the South Atlantic, while central Atlantic levels were lower than those observed near the South American and European coasts (figure 1). Elevated

ratios of 8:2 to 10:2 relative to 6:2 FTOH compared with source regions indicate that PFASs in this area mainly originate from long-range atmospheric transport. Comparison with previously reported data shows no significant decline in background atmospheric PFAS levels following the phase-out of perfluorooctane sulfonyl fluoride-based chemicals. These findings provide further evidence that neutral PFASs are a dominant driver of PFAS contamination in the global ocean through atmospheric transport.

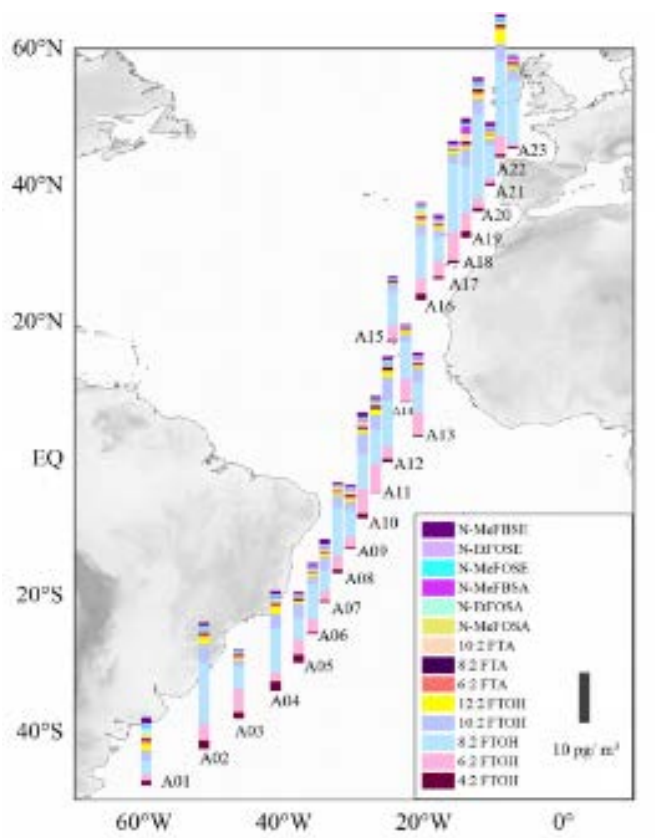


Figure 1: Concentrations (pg m^{-3}) and composition of individual PFASs in the marine atmosphere along the Atlantic transect during POLARSTERN cruise PS135.

WASCAL Floating University

The second leg of the Atlantic transit (PS135/2, March 28 – April 11, 2023, Mindelo to Bremerhaven) successfully implemented the third edition of the WASCAL Floating University. This academic training cruise served as a crucial component of the international master research program “Climate Change and Marine Sciences” (MRP-CCMS) based at the Atlantic Technical University of Cabo Verde (UTA)

and funded by the German Federal Ministry of Research, Technology and Space (BMFTR). The program is endorsed as an official UN Ocean Decade Project and combines a research expedition with academic curricular education to maximize benefits for both capacity building and ongoing scientific efforts in the region.

The Floating University hosted 12 West African M.Sc. students, supported by 9 scientists and a technician from various international institutes (figure 2). Theoretical instruction before and during the expedition addressed core curriculum modules, including Ocean Observations, Hydroacoustics in fisheries and marine ecology, and Communication and scientific writing. Students gained practical experience by rotating through dedicated research modules: oceanography, surface ocean biogeochemistry, marine ecology, microbiology, and science communication. Exercises such as the creation of short films to effectively communicate scientific concepts to the public were also carried out during the expedition. One student also collected data for her M.Sc. thesis during the cruise.



Figure 2: Group picture of the science crew onboard POLARSTERN cruise PS135/2 (left) and preparation of an Argo Float deployment by two WASCAL students (right).

Besides underway measurements, approximately 40 hours of station time were utilized for data collection (e. g., CTD, multinet, float deployments and recoveries). Station work was carried out daily, including extended biogeochemical and ecological samplings at the crucial long-term time series stations CVOO (Cape Verde Ocean Observatory) and ESTOC (European Station of Time-Series in the Ocean of the Canary Islands). Key activities included hydrographic profiling using the CTD rosette water sampler and ADCP measurements, revealing strong mesoscale variability, such as a cyclonic eddy north of the Canary Islands. Biogeochemical underway measurements tracked the transition from tropical waters to temperate regimes, clearly identifying a pronounced spring bloom event in the Bay of Biscay indicated by high dissolved oxygen and low pCO₂ values.

Marine ecology efforts included the deployment of a MultiNet to collect 60 zooplankton samples across different depth layers, revealing shifts from

oligotrophic subtropical ecosystems dominated by copepods to gelatinous zooplankton transition zones, and finally North Atlantic species associated with the spring bloom. Furthermore, the expedition contributed to global observation programs through the deployment of 5 new Argo profiling floats and the recovery of 2 existing floats.

By combining academic training with efficient data collection along the transit, PS135/2 proved the floating university model in advancing both regional oceanographic research and capacity development in West Africa.

References

Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Polar Research and Supply Vessel POLARSTERN Operated by the Alfred-Wegener-Institute, *Journal of large-scale research facilities* 2017, 3, A119, doi:10.17815/jlsrf-3-163.

Felden J, Möller L, Schindler U, et al., PANGAEA - Data Publisher for Earth & Environmental Science, *Scientific Data* 2023, 10, 347, doi:10.1038/s41597-023-02269-x.

Locarnini RA, Mishonov AV, Baranova OK, et al., *World Ocean Atlas 2018, Volume 1: Temperature*, NOAA Atlas NESDIS 2019, 81, doi:10.25923/e5rn-9711.

Wilkinson MD, Dumontier M, Aalbersberg IJ, et al., The FAIR Guiding Principles for scientific data management and stewardship, *Scientific Data* 2016, 3, 160018, doi:10.1038/sdata.2016.18.

Zweng MM, Reagan JR, Seidov D, et al., *World Ocean Atlas 2018, Volume 2: Salinity*, NOAA Atlas NESDIS 2019, 82, doi:10.25923/9pgv-1224.

Scientific Output

List of Publications

Fiedler B, Monteiro I, Almeida C, et al., 20 Years of Partnership in Marine Sciences Between Cabo Verde and Germany: From Ideas, Opportunities, and Observations to Long-Term and Sustained Capacity Sharing, *Oceanography* 2025, 38(1), doi: 10.5670/oceanog.2025.127.

GEBCO Bathymetric Compilation Group 2025, The GEBCO_2025 Grid – a continuous terrain model for oceans and land at 15 arc-second intervals, 2025, doi: 10.5285/37C52E96-24EA-67CE-E063-7086ABC05F29.

Traore S, Vertical migration and distribution of zooplankton along a latitudinal transect in the eastern North Atlantic, Master's Thesis 2023, Universidade Técnica do Atlântico, Mindelo, Cabo Verde, <https://wascalcv.org/theses.html>.

List of conference presentations

2025 | **20 Years of Partnership in Marine Sciences between Cabo Verde and Germany – from Projects to Long-Term and Sustained Capacity Sharing** One Ocean Science Congress, Nice, France.

2024 | **The Evolving WASCAL Network of Early Career Ocean Professionals in West Africa** UN Ocean Decade Conference, Barcelona, Spain.

2023 | **WASCAL Floating University** EuroSea Symposium on Ocean Observing and Forecasting, UNESCO, Paris, France.

Data

Multibeam bathymetry raw data (PS135/1):
<https://doi.org/10.1594/PANGAEA.958676>

Multibeam bathymetry processed data (PS135/1):
<https://doi.org/10.1594/PANGAEA.961241>

Multibeam bathymetry raw data (PS135/2):
<https://doi.org/10.1594/PANGAEA.958677>

Multibeam bathymetry processed data (PS135/2):
<https://doi.org/10.1594/PANGAEA.961240>

Whale sightings (PS135/1):
<https://doi.org/10.1594/PANGAEA.964778>

Whale sightings (PS135/2):
<https://doi.org/10.1594/PANGAEA.964873>

Physical Oceanography (Thermosalinograph, PS135/1):
<https://doi.org/10.1594/PANGAEA.964294>

Physical Oceanography (Thermosalinograph, PS135/2):
<https://doi.org/10.1594/PANGAEA.964295>

Physical oceanography (MIDAS SVP):
PANGAEA submission in prep.

Physical oceanography (CTD):
<https://osis.geomar.de/> (PANGAEA submission in prep.)

Chemical Oceanography (samples):
<https://osis.geomar.de/> (PANGAEA submission in prep.)

Marine Ecology (Zooplankton data):
ECOTAXA submission in prep.

Marine Ecology (hydroacoustic biomass data):
PANGAEA submission in prep.

Cruise Report

PS135: https://doi.org/10.57738/BzPM_0779_2023

PS136 and MSM108

Time-Series Studies at the LTER (Long-Term Ecological Research) Observatory HAUSGARTEN

Author

**Alfred Wegener Institute Helmholtz Center for Polar and Marine Research (AWI) |
Bremerhaven, Germany**
T. Soltwedel

Rationale

The expeditions RV Maria S. Merian expedition MSM108 (6th June – 3rd July 2022, Tromsø – Tromsø) and RV Polarstern PS136 (22nd May – 19th June 2023, Bremerhaven – Bremerhaven) to the Fram Strait between Greenland and the Svalbard archipelago contributed to various large national and international research and infrastructure projects (FRAM, MUSE, ARCHES, iFOODis, INTAROS, HiAOOS, ICOS, SIOS) as well as to the Helmholtz research programme “Changing Earth – Sustaining our Future” of the AWI. Within Topic 6 “Marine and Polar Life: Sustaining Biodiversity, Biotic Interactions and Biogeochemical Functions” (Subtopics 6.1 “Future ecosystem functionality” and 6.3 “The future biological carbon pump”) of the research programme, ecosystem shifts in the pelagic and deep ocean associated with water temperature increase and sea ice retreat were identified and quantified, and feedback processes on oceanographic processes were investigated. These studies included the identification of spatial and temporal developments in the function of selected pelagic and benthic communities. Within Subtopic 6.4 “Use and misuse of the ocean: Consequences for marine ecosystems”, the input of plastic waste into the ocean, the vertical fluxes of plastic from the sea surface to the seafloor, and the interaction between plastic and marine biota were investigated.

The work supported the time-series studies at the LTER (Long-Term Ecological Research) observatory HAUSGARTEN (Soltwedel et al., 2016), where we document Global Change induced environmental variations on a polar deep-water ecosystem. This work was carried out in close co-operation between the

HGF-MPG Research Group on Deep-Sea Ecology and Technology, the Working Group PEBCAO (“Phytoplankton Ecology and Biogeochemistry in the Changing Arctic Ocean”) at AWI, and the former Helmholtz Young Investigators Group SEAPUMP (“Seasonal and regional food web interactions with the biological pump”), representing a joint effort between the AWI, the MARUM – Center for Marine Environmental Sciences and the University of Bremen.

The expeditions were further used to accomplish installations for the HGF infrastructure project FRAM (FRontiers in Arctic marine Monitoring; Soltwedel et al., 2013). The FRAM Ocean Observing System aims at permanent presence at sea, from surface to depth, for the provision of near real-time data on Earth system dynamics, climate variability and ecosystem change. FRAM serves national and international tasks towards a better understanding of the effects of change in ocean circulation, water mass properties and sea-ice retreat on Arctic marine ecosystems and their main functions and services. FRAM implements existing and next-generation sensors in observatory platforms, allowing synchronous observation of relevant ocean variables as well as the study of physical, chemical and biological processes in the ocean. Experimental and event-triggered platforms complement the observational platforms. Products of the infrastructure are continuous long-term data with appropriate resolution in space and time, as well as ground-truthing information for ocean models and remote sensing.

Ecological long-term studies in the marine Arctic

The marine Arctic has played an essential role in the history of our planet over the past 130 million years and contributes considerably to the present functioning of the Earth and its life. The past decades have seen remarkable changes in key arctic variables, including a decrease in sea-ice extent and sea-ice thickness, changes in temperature and salinity of arctic waters, and associated shifts in nutrient distributions. Since arctic organisms are highly adapted to extreme environmental conditions with strong seasonal forcing, the accelerating rate of recent climate change challenges the resilience of arctic life. The stability of a number of arctic populations and ecosystems is probably not strong enough to withstand the sum of these factors, which might lead to a collapse of subsystems.

To detect and track the impact of large-scale environmental changes in the transition zone between the northern North Atlantic and the central Arctic Ocean, and to determine experimentally the factors controlling deep-sea biodiversity, the Alfred Wegener Institute Helmholtz Center for Polar and Marine Research (AWI) established the deep-sea observatory HAUSGARTEN, which constitutes the first, and until now only open-ocean long-term observatory in a polar region (Soltwedel et al., 2005).

HAUSGARTEN is located in the eastern Fram Strait and includes 21 permanent sampling sites along a depth transect (250–5500 m) and along a latitudinal transect following the 2500 m isobath crossing the central HAUSGARTEN station (Figure 1).

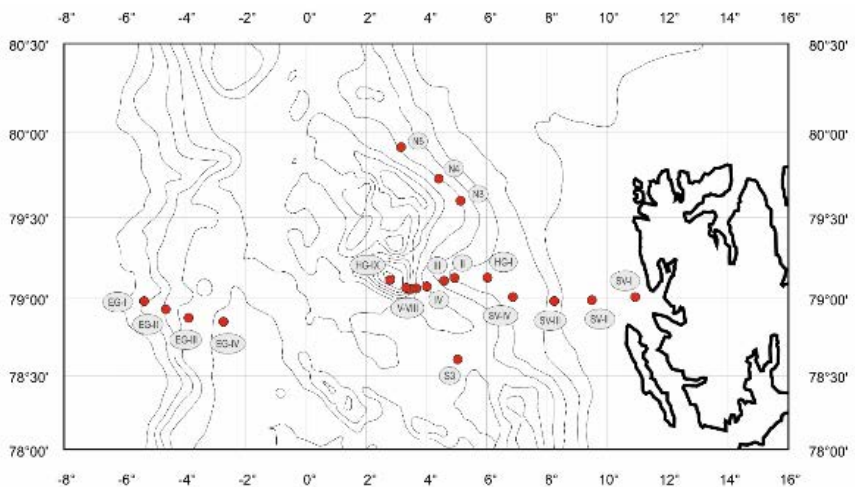


Figure 1: Permanent sampling sites of the LTER Observatory HAUSGARTEN in Fram Strait.

Multidisciplinary research activities at HAUSGARTEN cover almost all compartments of the marine ecosystem from the pelagic zone to the benthic realm. Regular sampling as well as the deployment of moorings and different stationary and mobile free-falling systems (Bottom-Lander, Benthic Crawler), which act as local observation platforms, have taken place since the observatory was established in 1999. Frequent visual observations with towed photo/video systems allow the assessment of large-scale epibenthic distribution patterns as well as their temporal development.

In the first ten years of time-series work at HAUSGARTEN there was a strong focus on the benthos. Spatial and temporal variations were studied for all benthic organism size classes including the sediment-dwelling bacteria, meiofauna, macrofauna, and megafauna. Sediment samples were analysed for a variety of parameters indicating the input of organic matter (food) to the benthos as well as benthic activity and biomass to assess the eco-status at the deep seafloor. Seafloor carbon mineralization was studied *in situ* at sites with varying sea-ice conditions. Moorings equipped with sediment traps provided data on particle fluxes to the deep seafloor. To assess background data on the overall hydrographic regime at HAUSGARTEN observatory CTD casts were regularly conducted during the annual expeditions.

Since 2009, the investigations have been expanded including a wide range of work in the pelagic to holistically record natural and anthropogenic changes in the Arctic marine ecosystem from the sea surface to the deep seafloor. The pelagic work combined classical bulk measurements of biogeochemical parameters, microscopy, optical methods, satellite observations, and molecular genetic approaches in a holistic approach. By doing so, this work compiled comprehensive information on annual variability in phyto- and zooplankton composition, primary production, and bacterial activity. Some specific experimental work during the expeditions MSM108 and PS136 were carried out to generate data which helps to understand the interactive effects of rising temperatures and nitrogen limitation on the structural composition of arctic microplankton communities.

Data availability

Only a minor part of the samples taken during the expeditions were analysed on board, while the majority of samples was processed and further analysed at the home labs within approximately one year after the cruise. The full data sets are usually available about 2–3 years after the cruise. All data retrieved during MSM108 and PS136 were or will be archived, published and disseminated according to international standards by the World Data Center PANGAEA Data Publisher for Earth & Environmental Science (www.pangaea.de). Benthic data was also deposited in CRITTERBASE at AWI, seafloor still images were uploaded to the online image database BIIGLE, and DNA sequences of benthic larvae and recruits collected during the expeditions were archived in GenBank. Molecular data (DNA, RNA) from the cruise will be archived, published and disseminated within one of the repositories of the International Nucleotide Sequence Data Collaboration (INSDC, www.insdc.org) comprising of EMBL-EBI/ENA, GenBank and DDBJ.

References

Soltwedel T, Bauerfeind E, Bergmann M, Budaeva N, Hoste E, Jaeckisch N, Juterzenka K v, Matthießen J, Mokievsky V, Nöthig E-M, Quéric N, Sablotny B, Sauter, E, Schewe I, Urban-Malinga B, Wegner J, Włodarska-Kowalczyk M & Klages M, HAUSGARTEN: multidisciplinary investigations at a deep-sea, long-term observatory in the Arctic Ocean, *Oceanography* 2005, 18 (3), 46–61, doi: 10.5670/oceanog.2005.24.

Soltwedel T, Schauer U, Boebel O, Nöthig E-M, Bracher A, Metfies K, Schewe I, Klages M & Boetius A, FRAM - FRontiers in Arctic marine Monitoring: Permanent Observations in a Gateway to the Arctic Ocean, *OCEANS – Bergen, 2013 MTS/ IEEE*, doi: 10.1109/OCEANS-Bergen.2013.6608008.

Soltwedel T, Bauerfeind E, Bergmann M, Bracher A, Budaeva N, Busch K, Cherkasheva A, Fahl K, Grzelak K, Hasemann C, Jacob M, Kraft A, Lalande C, Metfies K, Nöthig E-M, Meyer K, Quéric NV, Schewe I, Wlodarska-Kowalczyk M & Klages M, Natural variability or anthropogenically-induced variation? Insights from 15 years of multidisciplinary observations at the arctic open-ocean LTER site HAUSGARTEN, *Ecological Indicators* 2016, 65, 89–102, doi: 10.1016/j.ecolind.2015.10.001.

Scientific Output

List of Publications

(selected peer-reviewed publications from the time-series work at LTER HAUSGARTEN for the last 5 years)

Meyer-Kaiser KS, Nuñez K, Soltwedel T & Bergmann M, Long-term changes in deep-sea megafauna community structure in the eastern Fram Strait (Arctic Ocean), *Marine Ecology Progress Series*, 2025, 770, doi: 10.3354/meps14933.

Schnier J, Soltwedel T, Grzelak K, Górská B, Dannheim J, Mokievsky V, Martínez Arbizu P & Hasemann C, Deep-sea nematode community changes over two decades at HAUSGARTEN observatory (Fram Strait, Arctic Ocean), *Marine Ecology Progress Series*, 2025, 770, doi: 10.3354/meps14948.

Meyer-Kaiser KS, Schrage K & Bergmann M, Hard-bottom communities in the deep Fram Strait: patterns, processes, and looming questions, *Deep-Sea Research Part II*, 2025, 222, doi: 10.1016/j.dsr2.2025.105506.

Ruhl HA, Huffard CL, Messié M, Connolly TP, Soltwedel T, Wenzhöfer F, Johnson RJ, Bates NR, Hartman S, Flohr A, Mawji EW, Karl DM, Potemra J, Santiago-Mandujano F, Ross T & Smith KL, Decadal change in deep-ocean dissolved oxygen in the North Atlantic Ocean and North Pacific Ocean, *Deep-Sea Research Part I* 2025, 223, doi: 10.1016/j.dsr.2025.104534.

Priest T, Oldenburg E, Popa O, Dede B, Metfies K, von Appen W-J, Torres-Valdés S, Bienhold C, Fuchs BM, Amann R, Boetius A & Wietz M, Seasonal recurrence and modular assembly of an Arctic pelagic marine microbiome, *Nature Communications* 16, 2025, 1326, doi: 10.1038/s41467-025-56203-3.

Rufas Blanco A, Khatiwala S, Bisson KM, Martin AP & Bouman HA, Can we Constrain Geographical Variability in the Biological Carbon Pump's Transfer Efficiency from Observations?, *Geophysical Research Letters* 52, 2025, doi: 10.1029/2024GL111203.

Ramondenc S, Eveillard D, Metfies K, Iversen MH, Nöthig E-M, Piepenburg D, Hasemann C & Soltwedel T, Unveiling pelagic-benthic coupling associated with the biological carbon pump in the Fram Strait (Arctic Ocean), *Nature Communications* 16, 2025, 840, doi: 10.1038/s41467-024-55221-x.

Roscher L, Nöthig E-M, Fahl K, Wekerle C, Krumpfen T, Hoppmann M, Knüppel N, Primke S, Gerdtz G & Bergmann M, Origin and intra-annual variability of vertical microplastic fluxes in Fram Strait, Arctic Ocean, *Science of The Total Environment* 958, 2025, 178035, doi: 10.1016/j.scitotenv.2024.178035.

Priest T, von Appen W-J, Oldenburg E, Popa O, Torres-Valdés S, Bienhold C, Metfies K, Boulton W, Mock T, Fuchs BM, Amann R, Boetius A & Wietz M, Atlantic water influx and sea-ice cover drive taxonomic and functional shifts in Arctic marine bacterial communities, *The ISME Journal* 17, 2023, 1612-1625, doi: 10.1038/s41396-023-01461-6.

Ramondenc S, Iversen MH & Soltwedel T, Long-term measurements reveal a 100-day lag between peaks in phytoplankton chlorophyll and benthic bacterial abundance in the Fram Strait, *ICES Journal of Marine Science* 81(8), 2024, 1647-1654, doi: 10.1093/icesjms/fsae113.

Tokuhiro K, Matsuno K, Onodera J, Sampei M, Fujiwara A, Harada N, Niehoff B, Nöthig E-M & Yamaguchi A, Sediment trap samples reveal regional differences in the population structure of *Calanus hyperboreus* from the Arctic Ocean, *Journal of Plankton Research* 46(2), 2024, 183-193, doi: 10.1093/plankt/fbad059.

Cardozo-Mino MG, Salter I, Nöthig E-M, Metfies K, Ramondenc S, Wekerle C, Krumpfen T, Boetius A & Bienhold C, A decade of microbial community dynamics on sinking particles during high carbon export events in the eastern Fram Strait, *Frontiers in Marine Science* 10, 2023, doi: 10.3389/fmars.2023.1173384.

Salter I, Bauerfeind E, Fahl K, Iversen MH, Lalande C, Ramondenc S, Von Appen W-J, Wekerle C & Nöthig E-M, Interannual variability (2000–2013) of mesopelagic and bathypelagic particle fluxes in relation to variable sea ice cover in the eastern Fram Strait, *Frontiers in Earth Sciences* 11, 2023, doi: 10.3389/feart.2023.1210213.

Gorska B, Gromisz S, Legeżyńska J, Soltwedel T & Włodarska-Kowalczyk M, Macrobenthic diversity response to the atlantification of the Arctic Ocean (Fram Strait, 79°N) – A taxonomic and functional trait approach, *Ecological Indicators* 144, 2022, doi: 10.1016/j.ecolind.2022.109464.

Ramondenc S, Nöthig E-M, Hufnagel L, Bauerfeind B, Busch K, Knüppel N, Kraft A, Schröter F, Seifert M & Iversen MH, Effects of Atlantification and changing sea-ice dynamics on zooplankton community structure and carbon flux between 2000 and 2016 in the eastern Fram Strait, *Limnology and Oceanography* 68(51), 2022, 539-553, doi: 10.1002/lno.12192.

Nöthig E-M, Ramondenc S, Haas A, Hehemann L, Walter A, Bracher A, Lalande C, Metfies K, Peeken I, Bauerfeind E & Boetius A, Summertime Chlorophyll a and Particulate Organic Carbon Standing Stocks in Surface Waters of the Fram Strait and the Arctic Ocean (1991–2015), *Frontiers in Marine Sciences* 7, 2020, doi: 10.3389/fmars.2020.00350.

Soltwedel T, Grzelak K & Hasemann C, Spatial and temporal variation in deep-sea meiofauna at the LTER Observatory HAUSGARTEN in Fram Strait (Arctic Ocean), *MDPI – Diversity* 12, 2020, 1–23, doi: 10.3390/d12070279.

List of conference presentations

(featuring the scientific output of the expeditions MSM108 and PS136)

2025 | **Accidental in-situ observations reveal previously unknown behavior type in cephalopods, relevant to benthic-pelagic coupling.** 17th Deep-Sea Biology Symposium, Hong Kong, China.

2025 | **Unlocking arctic biodiversity: A key to benthic macrofauna and biogeographic insights based on long-term studies.** 17th Deep-Sea Biology Symposium, Hong Kong, China.

2025 | **Consistency or change in the benthic deep-sea macrofauna.** 17th Deep-Sea Biology Symposium, Hong Kong, China.

2025 | **Hidden Diversity: Isopod Communities of the Deep Arctic Ocean.** The Crustacean Society Summer Meeting. Paris, France.

2024 | **Fluorinated Feedback Loop: Observations of Equal PFAS Import and Export Through the Fram Strait.** Symposium on Emerging Contaminants and Hazardous & Noxious Substances. PEOPLE 2024 Fall Online Symposium.

2024 | **PFAS Alternatives Require Consideration of New Pathways and Potential Consequences.** Northeast Conference on the Science of PFAS: Public Health & The Environment, Marborough, MA, USA.

2024 | **Leben am und im arktischen Tiefseeboden.** Offenes Haus, AWI Bremerhaven, Germany.

2024 | **Diversität freilebender Nematoden des arktischen Tiefseeobservatoriums LTER HAUSGARTEN.** LTER-D Jahrestagung, Umweltbundesamt UBA, Dessau, Germany.

2024 | **The 2023 additions to the Fram Strait and Kongsfjorden observational timeseries.** Arctic Science Summit Week, ASSW 2024, Edinburgh, UK.

2024 | **Microbial Seasonality in the Arctic and Antarctic Oceans: From Gene to Ecosystem.** Gordon Research Conference "Marine Microbes". Les Diablerets, Switzerland.

2024 | **Microbial Ecology of the Deep (and not so deep) Arctic Ocean.** HADAL Retreat, Danish Center for Hadal Research, Odense, Denmark.

2024 | **Low price and under the polar ice: Platform and sensor developments for deep ocean polar research.** Ocean Science Meeting, New Orleans, USA.

2023 | **Polarstern Expedition PS136 – A contribution to the ecological time-series studies at the LTER observatory HAUSGARTEN.** A-DBO Autumn Meeting, Sopot, Poland.

2023 | **Macrobenthic diversity response to the Atlantification of the Arctic Ocean (Fram Strait, 79° N).** Polar Symposium, Sopot, Poland.

2023 | **Mapping Arctic and Antarctic Seas with towed camera systems.** GEOHAB, La Reunión, France.

2023 | **Benthic Megafauna in the Arctic Ocean – A time series analysis.** LTER-D Annual Meeting, On-line Symposium.

2023 | **Benthische Megafauna im Arktischen Ozean – zukünftige Dominanz von Seegurken?** Naturwissenschaftlicher Verein, Bremen, Germany.

2023 | **Da ist der Wurm drin – Die Sandlückenfauna des Arktischen Tiefseebodens.** Naturwissenschaftlicher Verein, Bremen, Germany.

2023 | Macrobenthic diversity response to the Atlantification of the Arctic Ocean (Fram Strait, 79°N) – A functional approach. 6th Workshop on Trait-Based Approaches to Ocean Life, Copenhagen, Denmark.

2023 | The role of macrobenthos: providing resources and ecosystem function... Invertebrate Zoology Seminar, Lodz, Poland.

2023 | Winners and losers of Atlantification: The degree of ocean warming affects the structure of Arctic microbial communities. ASLO Aquatic Sciences Meeting, Palma de Mallorca, Spain.

2022 | DeepC3000 – large corrosion-free pressure housing made of ultra-high performance concrete (UHPC) for depths up to 3,000 m. IEEE Xplore, Oceans 2022, Hampton Roads, USA.

2022 | DeepC3000 – first deployment of a pressure housing made of UHPC for depths up to 3,000 m on a deep-sea mission using a carrier frame made of carbon reinforced concrete. IEEE Xplore, Oceans 2022, Hampton Roads, USA.

Data

Master track of Maria S. Merian cruise MSM108 in 1 sec resolution (zipped, 10.8 MB):
<https://doi.org/10.1594/PANGAEA.948122>

Master tracks in different resolutions of Maria S. Merian cruise MSM108, Tromsø – Tromsø, 2022-06-07–2022-07-02:
<https://doi.org/10.1594/PANGAEA.948123>

ADCP current measurements (38 kHz) during RV MARIA S. MERIAN cruise MSM108:
<https://doi.org/10.1594/PANGAEA.956600>

Continuous thermosalinograph oceanography along RV MARIA S. MERIAN cruise track MSM108:
<https://doi.org/10.1594/PANGAEA.956595>

Multibeam bathymetry raw data (Kongsberg EM712 entire dataset) of RV MARIA S. MERIAN during cruise MSM108:
<https://doi.org/10.1594/PANGAEA.965809>

Multibeam bathymetry raw data (Kongsberg EM 122 entire dataset) of RV MARIA S. MERIAN during cruise MSM108:
<https://doi.org/10.1594/PANGAEA.965808>

Megafauna density observed using OFOS at the station HAUSGARTEN-I, 2017-2022:
<https://doi.org/10.1594/PANGAEA.967215>

Multibeam bathymetry processed data (dataset compilation) of RV POLARSTERN & RV MARIA S. MERIAN during 44 cruises from 1984 to 2024, Fram Strait, Greenland Sea, Arctic Ocean:
<https://doi.pangaea.de/10.1594/PANGAEA.977481>

Master track of POLARSTERN cruise PS136 in 1 sec resolution (zipped, 101.2 MB):
<https://doi.org/10.1594/PANGAEA.962550>

Master tracks in different resolutions of POLARSTERN cruise PS136, Bremerhaven – Tromsø, 2023-05-22-2023-06-19:
<https://doi.org/10.1594/PANGAEA.962551>

Whale sightings during POLARSTERN cruise PS136:
<https://doi.org/10.1594/PANGAEA.972704>

Raw data of continuous VM-ADCP (vessel-mounted Acoustic Doppler Current Profiler) profile during POLARSTERN cruise PS136:
<https://doi.pangaea.de/10.1594/PANGAEA.961877>

Phytoplankton pigment and phytoplankton group chlorophyll-a concentrations during POLARSTERN cruise PS136 from North Sea to Fram Strait in May to June 2023 from HPLC analysis of water samples:
<https://doi.pangaea.de/10.1594/PANGAEA.983243>

Metadata from mooring F4-W-4 in the Fram Strait, July 2022 – June 2023:
<https://doi.org/10.1594/PANGAEA.974855>

Raw physical oceanography and ocean current velocity data from mooring HG-IV-FEVI-44 in the Fram Strait, July 2022 – June 2023:
<https://doi.org/10.1594/PANGAEA.974873>

Raw physical oceanography, bio-optical and biogeochemical data from mooring F4-S-6 in the Fram Strait, June 2022 – July 2023:
<https://doi.org/10.1594/PANGAEA.974875>

Total and phytoplankton group chlorophyll concentrations from underway spectrophotometry with water mass classification in the East Greenland Sea from Polarstern expeditions 2015–2024:
<https://doi.pangaea.de/10.1594/PANGAEA.983421>

A validation data set of phytoplankton pigment concentrations and phytoplankton groups measured on water samples collected from various expeditions:
<https://doi.org/10.1594/PANGAEA.982433>

Gridded hourly physical oceanography data from hydrographic moorings in the eastern Fram Strait between 1997–2024:
<https://doi.pangaea.de/10.1594/PANGAEA.983454>

Ocean Floor Observation and Bathymetry System (OFOBS) seafloor images of the Fram Strait collected during RV POLARSTERN cruise PS136:
<https://doi.org/10.1594/PANGAEA.971365>

Seafloor images collected along OFOBS profile PS136 during RV POLARSTERN cruise PS136:
<https://doi.org/10.1594/PANGAEA.971402>,
<https://doi.org/10.1594/PANGAEA.971403>,
<https://doi.org/10.1594/PANGAEA.971404>,
<https://doi.org/10.1594/PANGAEA.971405>,
<https://doi.org/10.1594/PANGAEA.971406>,
<https://doi.org/10.1594/PANGAEA.971407>,
<https://doi.org/10.1594/PANGAEA.971408>,
<https://doi.org/10.1594/PANGAEA.971409>,
<https://doi.org/10.1594/PANGAEA.971410>

Cruise Reports

MSM108: https://doi.org/10.48433/cr_msm108
PS136: https://epic.awi.de/id/eprint/58043/1/BzPM_0780_2023.pdf

PS137

Exploring Arctic Hydrothermal Vent Fields

Authors

Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany

V. Schlindwein, M. Schmidt-Aursch, M. Pilot, T. Isler, L. Böhringer, F. Warnke, E. Unland, L. Höppner

MARUM – Center for Marine Environmental Sciences | Bremen, Germany

M. Walter, J. Mette, E. Albers, G. Wegener, Q. Zhu

University of Bremen | Bremen, Germany

V. Schlindwein, N. Kaul

Woods Hole Oceanographic Institution | Woods Hole, USA

C. German, E. Albers, J. Seewald, M. Curran, M. Jakuba, V. Naklicki, A. Dalpe, M. Silvia, R. Loer

NASA Jet Propulsion Laboratory | Pasadena, USA

A. Klesh, A. Branch

Max Planck Institute for Marine Microbiology | Bremen, Germany

M. Molari, C. Klaembt

Universität Münster | Münster, Germany

F. Genske

Applied Physics Laboratory, University of Washington | Seattle, USA

L. Lindzey

PS137 goals and survey design

The expedition ALOIS (Arctic Lithosphere Ocean Interaction Study), PS137 on RV Polarstern, was a pioneering interdisciplinary study of the formation of new lithosphere at the Gakkel Ridge and its associated hydrothermal circulation. Twenty years ago, the AMORE expedition (Michael et al., 2003) discovered that ultraslow seafloor spreading at the Gakkel Ridge could not be explained by

traditional models and was accompanied by anomalously abundant hydrothermal activity (Edmonds et al., 2003). Despite these significant discoveries, subsequent research was limited by the lack of advanced deep-sea technology suitable for a fully ice-covered ocean. With the recent upgrade to a 5000m depth capability, PS137 was the first to deploy WHOI's mobile robotic platform, *Nereid Under Ice (NUI)*, to explore deep-sea vents in the Arctic Ocean. The expedition also used ocean-bottom seismometers (OBS) modified for recovery in sea ice. Joint operations with the Norwegian GoNorth campaign on board RV Kronprins Haakon featuring ROV Aegir6000, further enhanced our capabilities. PS137 was thus able to comprehensively study two of the few hydrothermal vent fields ever traced to their seafloor sources on ultraslow-spreading ridges, sampling them geophysically, biogeochemically and microbiologically.

Challenges and technological achievements of PS137

Unexpectedly severe sea ice conditions (90–100% ice cover) and a damage of RV Polarstern's bow thruster forced us to focus our survey at two locations, the Aurora vent site at the western end of Gakkel Ridge and Lucky Ridge in Lena Trough (Figure. 1), and to abandon seismic profiling, dredge operations and a more extensive science program along the Western Volcanic Zone of Gakkel Ridge and its 3°E boundary. Despite these challenges, we successfully conducted four deep dives with NUI, reaching bottom times of five hours, maximum dive depths of 4000 m and a maximum distance from the ship of 2.7 km. These dives included detailed seafloor mapping and successful in-situ sampling of vent fluids. All OBS were successfully recovered in difficult sea ice conditions providing valuable experience in different recovery strategies. We further recovered oceanographic moorings on Yermak Plateau.

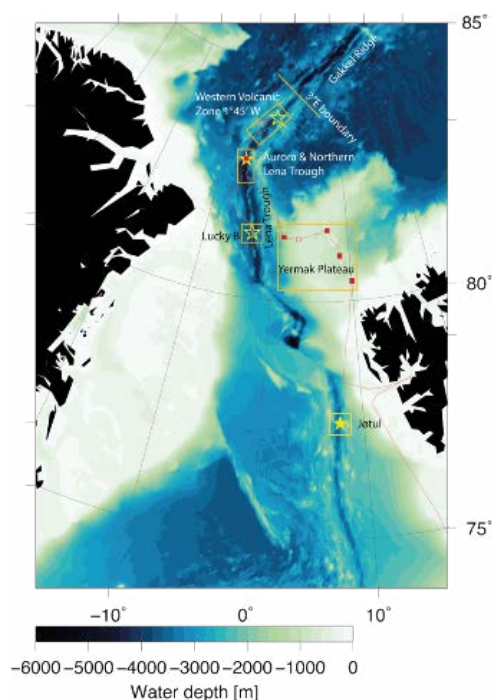


Figure 1: Cruise track of PS137. Stars: Hydrothermal plumes (open), confirmed hydrothermal vents (solid). Boxes: survey areas. Squares: oceanographic mooring recoveries.

Scientific highlights

Vent discovery, fluid and plume sampling at Aurora hydrothermal field (Figure 2)

A scientific highlight of PS137 was the discovery of seven new, actively venting hydrothermal chimneys at the Aurora vent field. These chimneys, aligned along an elevated ridge parallel to the Gakkel Ridge's strike direction, included a spectacular chimney that reached over 17 meters in height. High-resolution bathymetry and camera images enabled the creation of 3D textured models of these chimneys (Isler et al., 2024). Our vent fluid sampling included high-temperature 'black smoker' fluids (360°C), which were highly enriched in hydrogen (H_2), with ~50 mmol/L, and contained >1 mmol/L dissolved methane (CH_4) (Seewald et al., 2023; Klaembt et al., in prep.). The H_2 likely formed from reactions of circulating hydrothermal fluids with mantle peridotite located beneath the basaltic lavas observed at the seafloor (German et al., 2022). We also sampled lower-temperature fluids (126°C) co-located with the sampled high temperature vent, which had much less H_2 , suggesting rapid abiotic consumption during subseafloor mixing and cooling (German et al., in prep.).

Above Aurora, we re-investigated the hydrothermal plume's extent and composition via a one-year long mooring and eight CTD deployments. The plume

was unusually shaped, with limited lateral spread but a vertical rise of up to ~900 m, likely due to weak lateral currents and a weakly stratified water column (Walter et al., 2025). Dissolved H_2 and CH_4 were detected along with hydrothermal tracers, all confined to within ~1 km of the vent site (Klaembt et al., in prep.).

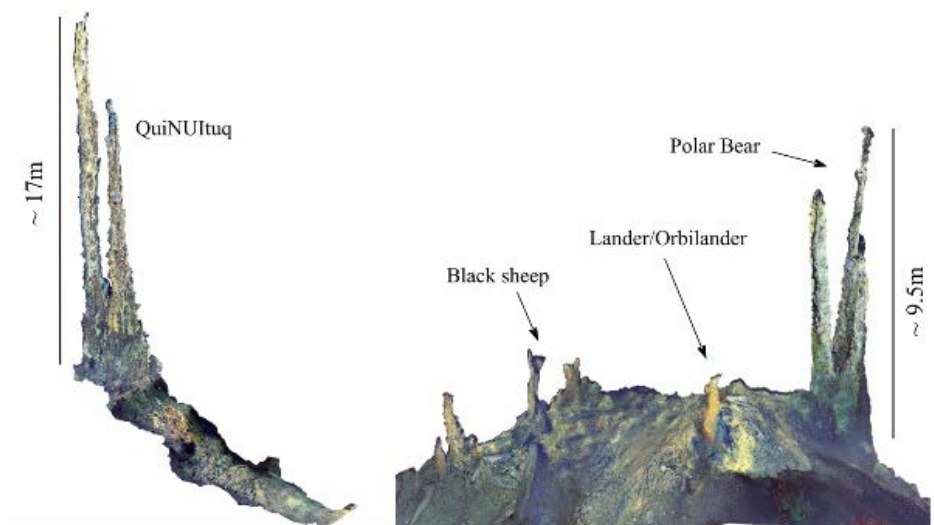


Figure 2: Snippets of the 3D textured model of the newly discovered hydrothermal chimneys at the Aurora vent field (from Isler et al., 2024).

Geophysical setting of Aurora hydrothermal field (Figure 3)

During OBS deployment, frequent earthquakes were recorded over a 12-month period (Pilot et al., in prep.). Seismicity near Gakkel Ridge aligned with fault systems that follow the ridge's strike, with a notable seismic gap at the axial volcanic ridge northeast of Aurora. A pronounced magnetic anomaly indicates robust magmatic crustal production there. The smaller positive magnetic anomaly at Aurora mound is clearly detached from the central magnetic anomaly of Gakkel Ridge. Seismic activity around Aurora showed irregular distribution, with a small gap northeast of the vent field. In Lena Trough, magnetic anomalies disappeared, and seismic activity deepened from 5–6 km to more than 12 km below the seafloor. The upper 5–6 km of the lithosphere in the Lena Trough show no earthquake activity. Aurora vent field is therefore positioned at the intersection of highly faulted Gakkel Ridge lithosphere - detached from its axial volcanic ridge - with the supposedly heavily serpentinised ultramafic lithosphere of Lena Trough. The heat supply for hydrothermal circulation may be locally confined to the Aurora mound, potentially indicated by a temperature-controlled lack of seismicity north of the vent field.

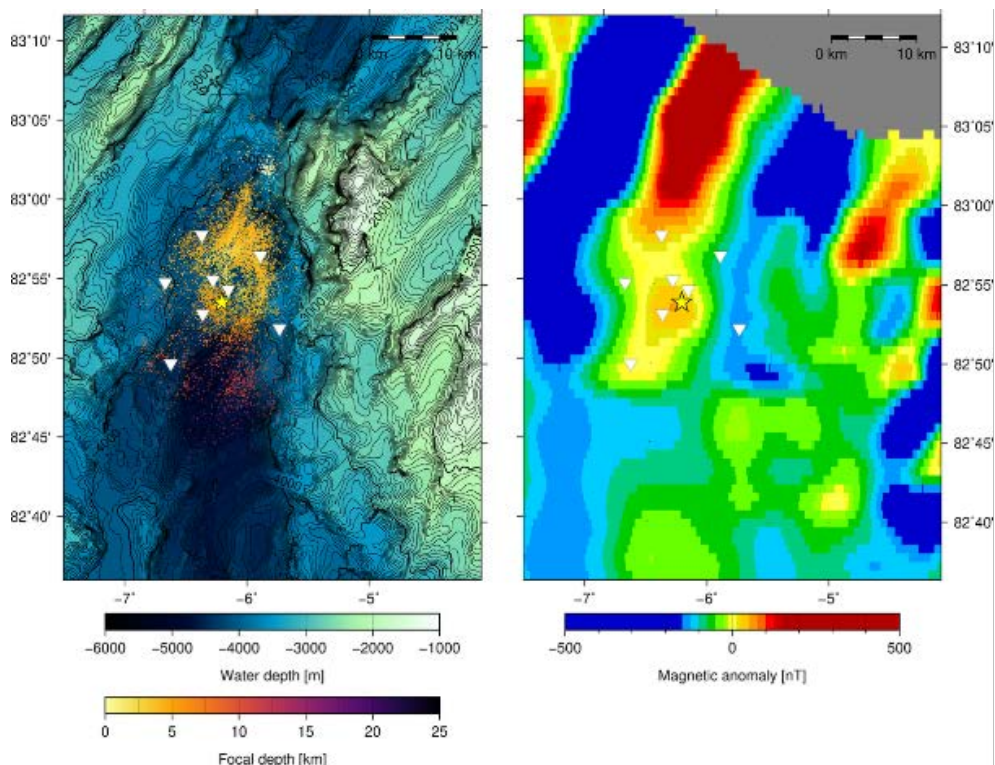


Figure 3: Left: Microseismicity around Aurora vent field (star) recorded by the network of OBS (triangles). Dots show 10247 earthquake foci with a rms <0.2 s, >10 phases and a location error <2 km, with magnitudes from -0.4 to 4. Right: Magnetic anomaly grid from the helicopter-borne surveys of PS137.

Discovery of the Lucky B vent site

Towards the end of the expedition, we discovered the Lucky B hydrothermal vent site in the Lena Trough at 81°N. While massive sulfides providing evidence for geologically-recent hydrothermal activity were dredged in 1999 (Snow et al., 2001), no detailed site characterization had previously been achieved. The Lucky B site lies on the western flank of the Lucky Ridge, a major peridotite outcrop in the central Lena Trough, making it one of fewer than ten known active ultramafic-hosted vent systems globally.

Seafloor investigations revealed diffuse, metal-poor venting with abundant fauna, massive sulfides, and hydrothermal chimneys extending laterally over at least 1.9 km (Albers et al., in press). Two distinct plumes were identified in the overlying water column, one of which showed pronounced redox and particle anomalies, along with unusually high concentrations of H_2 and CH_4 . Lucky B is thus identified as a complex “black smoker”-type system with multiple venting styles and fluid sources. Interestingly, it displayed low H_2 -to- CH_4 ratios and elevated CH_4 , suggesting potential involvement of sediments in subseafloor fluid-rock reactions.

Hydrothermal plume microbiology

Energy-rich compounds released by hydrothermal discharge can be utilized by chemosynthetic microbes to create biological hotspots in the otherwise energy-depleted deep ocean. In the Aurora hydrothermal plume, microbial activity was up to 13 times higher than in background seawater. Incubation experiments with plume water confirmed microbial H_2 consumption, indicating the presence of H_2 -oxidizing microorganisms (Klaembt et al., in prep.). Molecular analysis identified *Candidatus Sulfurimonas pluma* as the dominant species, and detected SUP05 sequences, suggesting sulfide oxidation within the plume.

In the Lucky B plume, microbial dark carbon fixation was tenfold higher relative to background seawater, demonstrating that the plume similarly stimulated chemoautotrophic microbial activity (Albers et al., in press). As with the Aurora plume, *Ca. S. pluma* and SUP05 were dominant in the microbial community. These findings demonstrate that hydrothermal chemical energy supports similar styles of autotrophic microbial growth at both basalt-hosted Aurora and peridotite-hosted Lucky B sites, fueling localized biomass production in the deep Arctic Ocean.

References

Albers E, Genske F, Seewald JS, Walter M, Mette J, Wegener G, Molari M, Klaembt C, Galluci L, Isler T, Böhringer L, Fitzsimmons JN, Gunnells S, Schlindwein V & German CR, Enigmatic H_2 - and CH_4 -rich hydrothermal plumes at the ultramafic-hosted Lucky B site, 81°N on Lena Trough, Arctic Ocean, Scientific Reports 2025, in press, doi:10.1038/s41598-025-19746-5.

Edmonds HN, et al., Discovery of abundant hydrothermal venting on the ultraslow-spreading Gakkel ridge in the Arctic Ocean, Nature 2003, 421, 252–256, doi: 10.1038/nature01351.

German CR, et al., Volcanically hosted venting with indications of ultramafic influence at Aurora hydrothermal field on Gakkel Ridge, Nature Communications 2022, 13, 6517 doi:10.1038/s41467-022-34014-0.

German CR, Seewald JS, et al., Vent-fluid geochemistry and detailed geologic setting of the Aurora hydrothermal field, Gakkel Ridge, in prep.

Isler T, Jakuba M, Kwasnitschka T, Purser A, Klesh A, Schlindwein V & German CR, High-resolution bathymetry coupled with 3D models of hydrothermal vents from opportunistically-acquired imagery: Aurora vent field, Arctic Ocean, Journal of Maps 2024, 20(1), doi:10.1080/17445647.2024.2404878.

Klaembt C, et al., Hydrogen oxidation fuels autotrophic carbon fixation and causes blooms of *Ca. Sulfurimonas pluma* in an Arctic hydrothermal vent plume, in prep.

Michael PJ, et al., Magmatic and amagmatic seafloor generation at the ultraslow-spreading Gakkel ridge, Arctic Ocean, *Nature* 2003, 423, 956–961, doi: 10.1038/nature01704.

Pilot M, Schmidt-Aursch MC, Eagles G & Schlindwein V, Volcanic and non-volcanic spreading modes at Aurora hydrothermal vent field, Gakkel Ridge, from a sub-sea ice microseismicity survey, *Geochemistry Geophysics Geosystems*, in prep.

Seewald J, German CR, Sylva S & Naklicki V, Exploring Hydrogen Rich Venting Beneath Ice on an Ocean World-Abiotic Processes in Subsurface Mixing Zones, *AGU Fall Meeting Abstracts* 2023, 331, P43D-3310.

Snow J, Hellebrand E, Jokat W & Mühe R, Magmatic and Hydrothermal Activity in Lena Trough, Arctic Ocean, *EOS* 2001, 82,17, 193–198.

Walter M, Türke A, Diehl A, German CR, Mertens C, Mette J, Monien P, Prause S, Sültenfuß J, Bach W, Schlindwein V & Boetius A, Properties and dispersal of a hydrothermal plume in a weakly stratified under-ice environment, *Geochemistry Geophysics Geosystems* 2025, 26, e2024GC012016, doi:10.1029/2024GC012016.

Scientific Output

List of Publications

Walter M, Türke A, Diehl A, German CR, Mertens C, Mette J, Monien P, Prause S, Sültenfuß J, Bach W, Schlindwein V & Boetius A, Properties and dispersal of a hydrothermal plume in a weakly stratified under-ice environment, *Geochemistry Geophysics Geosystems* 2025, 26, e2024GC012016, doi:10.1029/2024GC012016.

Isler T, Jakuba M, Kwasnitschka T, Purser A, Klesh A, Schlindwein V & German CR, High-resolution bathymetry coupled with 3D models of hydrothermal vents from opportunistically-acquired imagery: Aurora vent field, Arctic Ocean. *Journal of Maps* 2024, 20(1), doi:10.1080/17445647.2024.2404878.

Genske F & Albers E, Ultraslow crustal accretion at Gakkel Ridge and Lena Trough: basalt and peridotite geochemical trends evoked by the evolution of the Arctic spreading system, *Geochemistry Geophysics Geosystems* (in revision), submitted on 30/03/2025.

Albers E, Genske F, Seewald JS, Walter M, Mette J, Wegener G, Molari M, Klaembt C, Galluci L, Isler T, Böhringer L, Fitzsimmons JN, Gunnells S, Schlindwein V & German CR, Enigmatic H₂- and CH₄-rich hydrothermal plumes at the ultramafic-hosted Lucky B site, 81°N on Lena Trough, Arctic Ocean, *Scientific Reports* 2025, in press, doi:10.1038/s41598-025-19746-5.

List of conference presentations

2023 | Exploring hydrogen rich venting beneath ice on an ocean world – field report AGU Fall Meeting, San Francisco, USA.

2023 | Exploring hydrogen rich venting beneath ice on an ocean world: abiotic processes in subsurface mixing zones AGU Fall Meeting, San Francisco, USA.

2024 | Reuse and recycle: how the merging of opportunistic data could be used to produce a 3D model of complex seafloor topography at the Aurora vent field – Gakkel ridge, Arctic Ocean EGU General Assembly 2024, Vienna, Austria.

2024 | Discovery of the “Lucky B” ultramafic-hosted hydrothermal field in the ultraslow-spreading Lena Trough, Arctic Ocean EGU General Assembly 2024, Vienna, Austria.

2024 | Observations of deep near-inertial internal waves in the Eurasian Basin EGU General Assembly 2024, Vienna, Austria.

2024 | Exploring hydrothermal vent fields of the Arctic mid-ocean ridge system with ocean bottom seismology 39th General Assembly of the European Seismological Commission, Corfu, Greece.

2024 | Hydrothermal activity in an ice-covered ocean on Earth: H₂ and CH₄ venting in the Arctic Ocean AGU Fall Meeting, Washington D.C., USA.

2024 | Exploring the Aurora Vent Field: Four Thousand Meters Under Ice with the NUI Hybrid Remotely Operated Vehicle IEEE-AUV Conference, Boston, USA.

2024 | Four Thousand Meters Under Ice: Exploring Ice-Covered Chemosynthetic Ecosystems at the Aurora Vent Field with the NUI Hybrid Remotely Operated Vehicle Astrobiology Science Conference, Providence (RI), USA

2024 | **Exploring hydrogen-rich venting beneath an ice-covered ocean – on Earth**
Astrobiology Science Conference, Providence (RI), USA

2025 | **New aeromagnetic and seismological data reveal insights into the transition of Gakkel Ridge to Lena Trough** 10th International Conference on Arctic Margins, Bremen, Germany.

2025 | **Sneak peeks into the seafloor: studying deep-sea hydrothermal systems in the Arctic Ocean** 10th International Conference on Arctic Margins, Bremen, Germany.

2025 | **Ultraslow accretion of the Arctic crust: clues from basalt and peridotite geochemistry along the Gakkel-Lena Trough ridge system** 10th International Conference on Arctic Margins, Bremen, Germany.

2025 | **Crustal production at the ultraslow spreading Gakkel Ridge: a review of current geophysical knowledge** 10th International Conference on Arctic Margins, Bremen, Germany.

Data

Hydrothermal plume chemical characteristics of from CTD water samples at the Lucky B hydrothermal field:
<https://doi.pangaea.de/10.1594/PANGAEA.983491>

In situ water column sensor data from NUI dive 046 at the Lucky B hydrothermal field:
<https://doi.pangaea.de/10.1594/PANGAEA.983459>

Incubation results on carbon uptake rates in plume waters collected by CTD from the Lucky B hydrothermal field:
<https://doi.pangaea.de/10.1594/PANGAEA.983458>

Miniature Autonomous Plume recorder (MAPR) data from RV POLARSTERN cruise PS137 at Lucky B site:
<https://doi.pangaea.de/10.1594/PANGAEA.983450>

Physical oceanography during RV POLARSTERN cruise PS137 at Lucky B site:
<https://doi.pangaea.de/10.1594/PANGAEA.983341>

CTD bottle data from RV POLARSTERN cruise PS137 at Lucky B site:
<https://doi.pangaea.de/10.1594/PANGAEA.983377>

Raw physical oceanography and ocean current velocity data from mooring AURORA1 on the Gakkel Ridge, Arctic Ocean, July 2022 – July 2023:
<https://doi.pangaea.de/10.1594/PANGAEA.974796>

Current meter velocities from mooring AURORA1 recovered during RV POLARSTERN cruise PS137:
<https://doi.org/10.1594/PANGAEA.974042>

Seafloor images (OFOBS):
<https://doi.org/10.1594/PANGAEA.971422>

Video along NUI profile 045 during POLARSTERN cruise PS137:
<https://doi.org/10.1594/PANGAEA.971307>

Video along NUI profile 044 during POLARSTERN cruise PS137:
<https://doi.org/10.1594/PANGAEA.971306>

Ocean bottom seismometer (OBS):
<https://doi.org/10.14470/9I763612>
<https://doi.pangaea.de/10.1594/PANGAEA.984603>

Sediment echosounder raw data (Atlas Parasound P70 echosounder entire dataset) of RV POLARSTERN during cruise PS137:
<https://doi.org/10.1594/PANGAEA.974473>

Multibeam bathymetry processed data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS137, Western Gakkel Ridge, Arctic Ocean:
<https://doi.org/10.1594/PANGAEA.963220>

Cruise Report

PS137: https://doi.org/10.57738/BzPM_0781_2023

PS138

Interdisciplinary long-term observations of a changing Central Arctic Ocean

Authors

**Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research |
Bremerhaven, Germany**

A. Boetius, C. Bienhold, M. Iversen, M. Nicolaus, B. Rabe, F. Wenzhöfer

Otto-von-Guericke University, | Magdeburg, Germany

C. Mehlmann, T. Richter

PS138 Shipboard Scientific Party

Overview and objectives

The rapid warming of the Arctic and sea ice retreat affect not only the hydrography of the Arctic Ocean, but also biogeochemical and biological processes. The expedition PS138 (ArcWatch-1) investigated the biology, chemistry and physics of sea ice, as well as the impact of sea ice retreat on the entire ocean system from the surface to the deep sea. The interdisciplinary scientific team studied the dynamics of first- and multiyear ice, as well as the role of summerly ice melt and re-growth in fall for the distribution of nutrients, productivity and the composition of pelagic and benthic communities, as well as the export of particulate matter to the deep sea. During the expedition PS80 (ARK27-3, IceArc) in 2012 (Boetius 2013), which took place during the largest documented sea ice minimum to date, substantial impacts on the ecosystem were found (Boetius et al., 2013). Eleven years later, the expedition PS138 assessed the current ecosystem state and enables comparative studies with previous decades. The team re-visited the same regions as in 2012 (Figure 1), and used interdisciplinary process studies to examine interactions between ice physics and biology, hydrography, biogeochemistry and biodiversity of the Arctic ecosystem, from the sea ice to the seafloor.

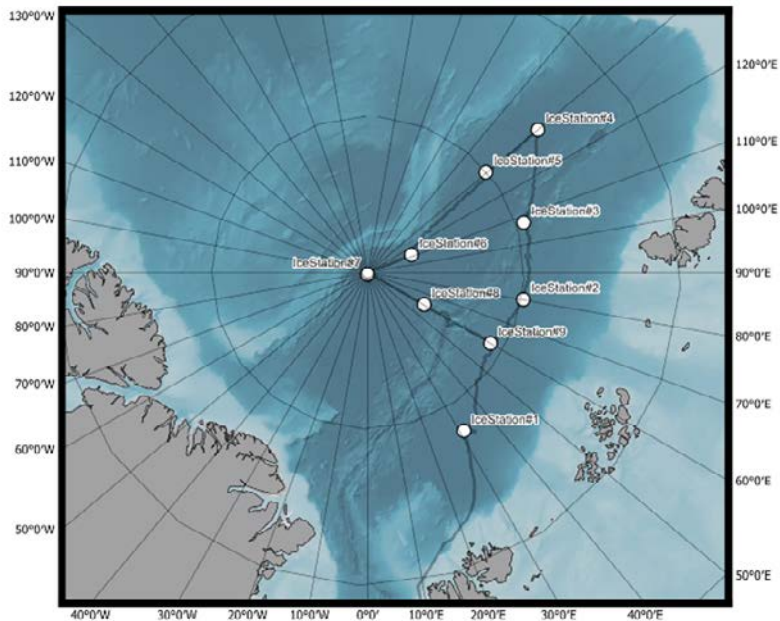


Figure 1: Cruise track (grey line) and ice stations visited during Polarstern expedition PS138 to the Central Arctic Ocean in summer 2023.

In addition, we repeated some studies at former MOSAiC sites (ice station #5). A total of 9 comprehensive ice stations (Figure 1) of about 3 days duration each were carried out during the expedition. At the ice stations, ice-physical and oceanographic measurements were carried out and samples were taken for biogeochemical and biological analyses (sea ice, water, seafloor). On 7 September 2023, the expedition reached the North Pole for its seventh ice station (Figure 2). biodiversity of the Arctic ecosystem, from the sea ice to the seafloor.



Figure 2: Left: RV Polarstern at the North Pole during expedition PS138 (E. Horvath). Right: Seafloor image at 4231 m water depth at the North Pole (PS138_151). Anemones and spoon worm traces, and some discolored patches (AWI OFOBS).

Our work included comparative studies between working areas in the marginal ice zone and areas covered by multiyear sea ice. The results of this expedition in summer 2023, which was marked by several anomalies in and around the Arctic, are an important contribution toward quantifying the effects of changes in sea ice cover on the Arctic Ocean and its ecosystems. The expedition is supported by the Helmholtz research program “Changing Earth – Sustaining our Future” Topic 2, Subtopics 1, 3 and 4, and Topic 6, Subtopics 1, 2 and 3, as well as various national and international programs.

Observations and preliminary results

The most notable observation, contrasting findings during PS80 in 2012, was the absence of the ice algae *Melosira*, both on the underside of the sea ice and at the seafloor. The large aggregates of *Melosira* that had been observed at the seafloor in 2012 were missing in 2023. We did observe discolored patches at the seafloor, which may be remnants of silica shells from previous *Melosira* falls. The absence of *Melosira* is likely attributed to unusual sea-ice drift patterns in 2023 that resulted in a shift of the origin of the sea ice that we encountered at our ice stations. In 2023, sea ice originated from far further west, i. e. the offshore Beaufort Sea, compared to other years, including 2012, where ice originated mostly from the Siberian shelves, allowing *Melosira* spores to be incorporated during ice formation.

Seafloor observations indicated the presence of much smaller algal aggregates, likely of different composition. At the same time, sediment chloroplastic pigment equivalents, as a proxy for organic matter input, were higher in 2023 compared to 2012, but less fresh, as indicated by lower chlorophyll-a proportions. Oxygen uptake rates were in a similar range, but slightly lower in 2023 compared to 2012, indicating similar carbon remineralization rates, but with elevated rates underneath algae deposits. The abundance and biomass of several benthic size classes showed shifts toward lower numbers in 2023, but further analyses are needed to identify the drivers of these differences. These currently take place in the framework of several PhD theses.

The observations and preliminary results illustrate how intricately linked the Central Arctic Ocean is through cryo-pelagic-benthic coupling, and how atmospheric and climatic shifts drive shifts across the ocean system.

In addition to repeat observations at the ice stations, PS138 contributed to exploratory work and mapping of unique habitats of the central Arctic Ocean, including seamounts at the Gakkel Ridge and the Lomonosov Ridge. Together with the sampling of benthic fauna across all size classes, this expedition marks an important contribution to mapping the under-sampled deep Arctic Ocean seafloor (Ramirez-Llodra et al., 2025).

Furthermore, the expedition supplied an important piece in the multi-year oceanographic time series along 60°E, surveying the Eurasian Basin and Transpolar Drift since 2005. First results indicate a shallowing of warm Atlantic Water and the lower halocline over the two decades up to 2024, likely associated with altered atmospheric circulation and ice drift, leading to a trend in upward Ekman Pumping.

As part of the side user proposal HybridIceOED, high-resolution observations of individual sea-ice floes, drifting in polynyas and in the marginal ice zone of the Arctic Ocean, were collected. Current continuum-based climate and sea-ice models neither resolve these floes nor adequately parameterize their interactions, which leads to systematic uncertainties in climate and weather projections. Observations during the expedition were directly used to calibrate a newly developed hybrid sea-ice model, which integrates discrete floe dynamics into continuum-mechanics frameworks. First analyses reveal systematic deviations from the classical Nansen rule: small, freely drifting floes often exhibit significantly larger drift angles relative to the wind than traditionally assumed. Numerical simulations confirm that these larger angles are driven by the presence of nearby larger floes, which modify the local ocean-current field and thereby influence the drift of smaller floes. These results provide new physical insights into marginal-ice-zone dynamics and highlight the need for hybrid modeling approaches; they represent an important step toward improving the representation of Arctic feedback processes in next-generation climate and weather models.

Final remarks

Many of the scientific disciplines contributed to a coordinated effort across several missions to the Central Arctic Ocean, including PS138 (ArcWatch-1) in 2023, PS144 (ArcWatch-2) in 2024, and PS149 (CONTRASTS) in 2025. The combined data provide a comprehensive spatial and temporal perspective on the central Arctic system, contributing valuable insights into processes and trends in this remote and rapidly changing region. Future missions are envisioned to follow up upon this work with continued observations in coming years, and a declaration of interest already across several disciplines.

References

Boetius A, The expedition of the research vessel “Polarstern” to the Arctic in 2012 (ARK-XXVII/3), *Berichte zur Polar- und Meeresforschung* = Reports on polar and marine research, 2013, Bremerhaven, Alfred Wegener Institute for Polar and Marine Research, 663, 166 p. doi: 10.2312/BzPM_0663_2013.

Boetius A, Albrecht S, Bakker K, Bienhold C, Felden J, Fernández-Méndez M, Hendricks S, Katlein C, Lalande C, Krumpen T, Nicolaus M, Peeken I, Rabe B, Rogacheva A, Rybakova E, Somavilla R, Wenzhöfer F & the RV Polarstern ARK27-3-Shipboard Science Party, Export of Algal Biomass from the Melting Arctic Sea Ice. *Science* 2013, 339, 1430–1432, doi: 10.1126/science.1231346.

Ramirez-Llodra E, Meyer HK, Bluhm BA, Brix S, Brandt A, et al., The emerging picture of a diverse deep Arctic Ocean seafloor: From habitats to ecosystems, *Elementa: Science of the Anthropocene* 2024, 12(1), doi: 10.1525/elementa.2023.00140.

Scientific Output

List of Publications

Kawaguchi Y, Hoppmann M, Shirasawa K, Rabe B & Kuznetsov I, Dependency of the drag coefficient on boundary layer, stability beneath drifting sea ice in the central Arctic Ocean, *Sci Rep* 2024, 14, 15446, doi: 10.1038/s41598-024-66124-8.

Rabault J, Taelman C, Idžanović M, et al., A position and wave spectra dataset of Marginal Ice Zone dynamics collected around Svalbard in 2022 and 2023, *Sci Data* 2024, 11, 1417, doi: 10.1038/s41597-024-04281-1.

Krumpen T, von Albedyll L, Bünger HJ, et al., Smoother sea ice with fewer pressure ridges in a more dynamic Arctic, *Nat. Clim. Chang.* 2025, 15, 66–72, doi: 10.1038/s41558-024-02199-5.

Albers E, Diehl A, Fitzsimmons JN, Jensen LT, Klein F, McDermott JM, Purser A, Seewald JS, Walter M, Wegener G, Bach W, Boetius A & German CR, Ultramafic-influenced submarine venting on basaltic seafloor at the Polaris site, 87°N, Gakkel Ridge, *Earth and Planetary Science Letters* 2025, 651, 119166, doi: 10.1016/j.epsl.2024.119166.

Mehlmann C & Richter T, Calibration of a hybrid sea ice model during an expedition to the Arctic. *Proceedings in Applied Mathematics and Mechanics* 2024, 24, e202400117, doi: 10.1002/pamm.202400117.

Wrissenberg M, Velocity and surface momentum fluxes in the central Arctic from observations and reanalysis, unpublished Bachelor thesis 2025, Carl von Ossietzky University of Oldenburg, 58 pp.

Schulte-Hillen R, Polar Ice to Abyssal Depths: Geographic and Vertical Dynamics of Microbial Community Patterns in a Changing Arctic, Master thesis 2024, Albert-Ludwigs-Universität Freiburg.

List of conference presentations

2023 | **Cryosphere sciences calling for international stewardship to limit impacts from melting ice**, Polar Forum Paris; incl. Workshop on Changing Arctic, Presentation to heads of states.

2023 | **Expedition “Arcwatch” to the central Arctic Ocean: biology, physics and chemistry from surface to seafloor**, Microbiological Colloquium, Oldenburg, Germany.

2024 | **Hotspots of life: Sponge grounds on volcanic seamounts in the Central Arctic Ocean**, Ocean Sciences Meeting, New Orleans, USA.

2024 | **Influence of light and silicic acid on the productivity of the Arctic phytoplankton community**, Silicamics, Brest, France.

2024 | **ONEBLUE – the Arctic Case Study**, EU Green Week, online.

2024 | **A hybrid ice-mélange model based on particle and continuum methods**, Polartagung, Rauris, Austria.

2024 | **Modeling and Numerical Analysis of sea ice**, Modeling, PDE analysis and computational mathematics in material science, Prague, Czech Republic.

2024 | **Scientific Machine Learning for sea ice**, 30 Years of Scientific Computing, Dortmund, Germany.

2024 | **Expedition ArcWatch – Arktischer Ozean im Wandel**, Gesellschaft für Geographie, Berlin, Germany.

2025 | **Deep-Sea Benthic Biodiversity and Function in a Changing Arctic Ocean**, Deep Sea Biology Symposium, Hong Kong, Special Administrative Region of the People's Republic of China.

2025 | **Consistency or Change in the Benthic Deep-Sea Macrofauna: An update from the Central Arctic Ocean**, Deep Sea Biology Symposium, Hong Kong, Special Administrative Region of the People's Republic of China.

2025 | **Hidden Diversity: Isopod Communities of the Deep Arctic Ocean**, The Crustacean Society Summer Meeting, Paris, France.

2025 | **A biogeographical inventory of benthic macrofauna based on long-term observations in the Arctic Ocean**, Deep Sea Biology Symposium, Hong Kong, Special Administrative Region of the People's Republic of China.

2025 | **Contrasting states of the Central Arctic Ocean in 2012 and 2023: Consequences for Deep-Sea Microbial Community Ecology and Ecosystem Functioning**, ICYMARE, Bremerhaven, Germany.

2025 | **Effects of sea ice decline and changing silicic acid availability on Central Arctic primary productivity**, GRC Polar Marine Science, Lucca, Italy.

2025 | **The role of dissolved organic compounds in the carbon cycle of the central Arctic Ocean**, ONEBLUE EU Project workshop, Athens, Greece.

2025 | **AWI activity in the European Arctic: an incomplete summary**, Arctic ROOS meeting, Brussels, Belgium.

2025 | **The New Arctic Amid Ongoing Changes: Sea Ice and Ocean Variability on Multiple Scales**, GRC Polar Marine Science, Lucca, Italy.

2025 | **Central Arctic observations by AWI: a physical oceanographer's perspective**, Presentation at NAMR, Kaohsiung, Taiwan.

2025 | **Central Arctic observations by AWI: a physical oceanographer's perspective**, Presentation at NSYSU, Kaohsiung, Taiwan.

2025 | **Changes in the central and Eurasian Arctic during the past two decades**, ISAR-8, Hachioji, Japan.

2025 | **A decade apart – Comparison of benthic communities in the deep Central Arctic Ocean**, 58th European Marine Biology Symposium, Bodo, Norway.

2025 | **Confusing Crustaceans 2025 – Identification workshop for peracarid crustaceans with international experts**, Wilhelmshaven, Germany.

2025 | **Numerical aspects of simulating large-scale sea-ice dynamics**, Workshop “Mathematical Advances in Geophysical Fluid Dynamics”, Oberwolfach, Germany.

2025 | **A Surface Crouzeix–Raviart Element for Geophysical Flow Problems**, GAMM Conference, Poznań, Poland.

2025 | **Development of a GPU accelerated dynamical core for sea ice**, GAMM Conference, Poznań, Poland.

2025 | **Changing polar oceans – from discovery to conservation of life under the ice**, Invited seminar, Stanford University, USA.

2025 | **Changing polar oceans – from discovery to conservation of life under the ice**, Invited seminar, Wise Program, USC, USA.

2025 | **Can the Arctic still be saved?** Paris-Saclay Summit, France

Data

Also see:

<https://www.pangaea.de/?q=ps138>

Master tracks

Master tracks in different resolutions of POLARSTERN cruise PS138, Tromsø – Bremerhaven, 2023-08-02–2023-10-01:

<https://doi.pangaea.de/10.1594/PANGAEA.963843>

Master track of POLARSTERN cruise PS138 in 1 sec resolution (zipped, 222.6 MB):

<https://doi.org/10.1594/PANGAEA.963840>

Bathymetry and echosounder

Multibeam bathymetry processed data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS138, Arctic Ocean:

<https://doi.pangaea.de/10.1594/PANGAEA.971589>

Multibeam bathymetry processed data (dataset compilation) of RV POLARSTERN & RV MARIA S. MERIAN during 44 cruises from 1984 to 2024, Fram Strait, Greenland Sea, Arctic Ocean:

<https://doi.pangaea.de/10.1594/PANGAEA.977481>

Multibeam bathymetry raw data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS138:

<https://doi.pangaea.de/10.1594/PANGAEA.963722>

Sediment echosounder raw data (Atlas Parasound P70 echosounder entire dataset) of RV POLARSTERN during cruise PS138:

<https://doi.pangaea.de/10.1594/PANGAEA.973444>

Seafloor images

Ocean Floor Observation and Bathymetry System (OFOBS) seafloor images of the Central Arctic Ocean collected during RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971424>

Seafloor images collected along OFOBS profile PS138_10-1 during RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971423>

Seafloor images collected along OFOBS profile PS138_102-1 during RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971439>

Seafloor images collected along OFOBS profile PS138_126-1 during RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971434>

Seafloor images collected along OFOBS profile PS138_127-1 during RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971435>

Seafloor images collected along OFOBS profile PS138_132-1 during RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971441>

Seafloor images collected along OFOBS profile PS138_151-1 during RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971443>

Seafloor images collected along OFOBS profile PS138_180-1 during RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971442>

Seafloor images collected along OFOBS profile PS138_198-1 during RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971440>

Seafloor images collected along OFOBS profile PS138_199-1 during RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971445>

Seafloor images collected along OFOBS profile PS138_202-1 during RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971444>

Seafloor images collected along OFOBS profile PS138_203-1 during
RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971446>

Seafloor images collected along OFOBS profile PS138_216-1 during
RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971447>

Seafloor images collected along OFOBS profile PS138_34-1 during
RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971433>

Seafloor images collected along OFOBS profile PS138_51-1 during
RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971437>

Seafloor images collected along OFOBS profile PS138_53-1 during
RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971438>

Seafloor images collected along OFOBS profile PS138_78-1 during
RV POLARSTERN cruise PS138:
<https://doi.pangaea.de/10.1594/PANGAEA.971436>

Buoy data

A subset of temperature and heating-induced temperature difference profiles from
6 SIMBA-type sea ice mass balance buoys deployed in the central Arctic Ocean,
August 2023 – April 2024:
<https://doi.pangaea.de/10.1594/PANGAEA.967430>

Snow depth, sea ice thickness and interface temperatures derived from
measurements of SIMBA buoy 2023T100:
<https://doi.pangaea.de/10.1594/PANGAEA.973345>

Snow depth, sea ice thickness and interface temperatures derived from
measurements of SIMBA buoy 2023T102:
<https://doi.pangaea.de/10.1594/PANGAEA.973338>

Snow depth, sea ice thickness and interface temperatures derived from
measurements of SIMBA buoy 2023T104:
<https://doi.pangaea.de/10.1594/PANGAEA.973343>

Snow depth, sea ice thickness and interface temperatures derived from measurements of SIMBA buoy 2023T105:
<https://doi.pangaea.de/10.1594/PANGAEA.973334>

Snow depth, sea ice thickness and interface temperatures derived from measurements of SIMBA buoy 2023T106:
<https://doi.pangaea.de/10.1594/PANGAEA.973329>

Snow depth, sea ice thickness and interface temperatures derived from measurements of SIMBA buoy 2023T107:
<https://doi.pangaea.de/10.1594/PANGAEA.973336>

Snow depth, sea ice thickness and interface temperatures derived from measurements of SIMBA buoy 2023T109:
<https://doi.pangaea.de/10.1594/PANGAEA.973327>

Snow depth, sea ice thickness and interface temperatures derived from measurements of SIMBA buoy 2023T110:
<https://doi.pangaea.de/10.1594/PANGAEA.973331>

Snow depth, sea ice thickness and interface temperatures derived from measurements of SIMBA buoy 2023T99:
<https://doi.pangaea.de/10.1594/PANGAEA.973340>

Snow height on sea ice and sea ice drift from autonomous measurements from buoy 2023S100, deployed during expedition PS138 (ArcWatch-1):
<https://doi.pangaea.de/10.1594/PANGAEA.973277>

Snow height on sea ice and sea ice drift from autonomous measurements from buoy 2023S101, deployed during expedition PS138 (ArcWatch-1):
<https://doi.pangaea.de/10.1594/PANGAEA.973279>

Snow height on sea ice and sea ice drift from autonomous measurements from buoy 2023S102, deployed during expedition PS138 (ArcWatch-1):
<https://doi.pangaea.de/10.1594/PANGAEA.973281>

Snow height on sea ice and sea ice drift from autonomous measurements from buoy 2023S103, deployed during expedition PS138 (ArcWatch-1):
<https://doi.pangaea.de/10.1594/PANGAEA.973291>

Snow height on sea ice and sea ice drift from autonomous measurements from buoy 2023S124, deployed during expedition PS138 (ArcWatch-1):
<https://doi.pangaea.de/10.1594/PANGAEA.973301>

Temperature

Temperature and salinity profiles from a free-falling profiler during POLARSTERN cruise PS138:

<https://doi.pangaea.de/10.1594/PANGAEA.967731>

Temperature anomalies in the Polaris hydrothermal plume, Gakkel Ridge:

<https://doi.pangaea.de/10.1594/PANGAEA.973617>

DOM

Pressure-induced leakage of dissolved organic matter (DOM) from diatom-bacteria aggregates:

<https://doi.pangaea.de/10.1594/PANGAEA.974878>

Whale sightings

Whale sightings during POLARSTERN cruise PS138:

<https://doi.pangaea.de/10.1594/PANGAEA.972703>

Cruise Report

PS138: https://doi.org/10.57738/BzPM_0788_2024

PS140

EASI-2 | East Antarctic Ice Sheet Instabilities – Research Cruise PS140 to the Indian sector of the Southern Ocean and the East Antarctic continental margin

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

M. Gutjahr

**Alfred-Wegener-Institute, Helmholtz Centre for Polar and Marine Research |
Bremerhaven, Germany**

O. Esper

University of Cologne | Cologne, Germany

M. Melles

And scientific participants of research cruise PS140 / EASI-2

Expedition EASI-2 (East Antarctic Ice Sheet Instability) was the second of three jointly designed Polarstern expeditions aiming to investigate the history of East Antarctic Ice Sheet (EAIS) instability and its interaction with changes in Southern Ocean (SO) circulation. Each of the three coordinated expeditions had its own research focus related to the potential instability of the EAIS during current and past climatic changes. Compared with the other two expeditions, EASI-2 focused most strongly on current processes in the Southern Ocean water column, observable modern nutrient availability with a particular emphasis on the delivery of essential micronutrients from the seafloor and East Antarctica. Two transects of the water column in the open ocean were realised to determine the structure, chemical composition and current circulation status in the study area. Analogous work on the East Antarctic shelf provided the proximal Antarctic perspective on both physical and chemical oceanographic trends that can be observed today in times of generally rising seawater temperatures, decreasing sea ice extent and a

decrease in the salinity of various water masses in the SO such as the Antarctic Bottom Water (AABW). At the majority of deep-water stations of the two transects, complementary sampling of deep marine sediments of up to 25 metres below the sea floor was carried out to trace changes in the properties of the water column at some locations spanning more than the last 800 thousand years. The sedimentary work following the cruise focusses on Pleistocene dynamics of oceanic fronts within the Antarctic Circumpolar Current, changes in sea surface water temperatures, the past carbon budget of the water column and past sea ice extent. On the East Antarctic shelf, obtained parasound profiles and sediment sampling allow answering questions about the history of the Quaternary ice sheet and past deep-water formation. In the south-eastern part of Prydz Bay, extensive sediment cores have also been obtained to reconstruct the Holocene climate evolution in the region at high temporal resolution. These cores are also very valuable because, in parallel to the marine work, the team of land geologists was able to obtain limnic and marine cores in a fjord near the Australian Davis Station during a land campaign lasting almost three weeks. Bridging the gap between terrestrial and marine climate reconstructions is a major overarching goal of the EASI expeditions.

One of the most outstanding feature of this expedition is the endeavour to closely link modern observations from water column work with past states of SO circulation modes by using a variety of state-of-the-art methods and/or proxies and sampling strategies. For example, we can quantify sedimentary diagenetic processes at many realised sampling sites, in parallel with the application of palaeoceanographic proxies, such as the recovery of authigenic (i. e. seawater-derived) trace metals (e. g. Nd & Pb). Various geochemical methods are applied to extracted material (water, ice and sediments) in the home laboratories in order to evaluate the reliability of marine sedimentary archives. Various palaeoceanographic reconstructions will be carried out. Our cruise section covers a range of climate zones, from the temperate latitudes north of the subtropical front, through all frontal systems of the Southern Ocean, to the East Antarctic Ice Sheet. The composition of the sediments is correspondingly diverse and ranges from purely biogenic to purely terrestrial sediments, with correspondingly variable diagenetic redox zonation in sampled sediment.

At the majority of the stations visited during EASI-2, an extended spectrum of sampling strategies was pursued:

- (1) By using the regular water sampler, the structure of the water column was first determined and water samples were taken for various applications.
- (2) The use of a trace metal clean water sampler allowed water samples to be taken for the reliable determination of various trace metals susceptible to contamination.

(3) The uppermost centimetres of the seafloor were sampled at a number of stations using a multi-corer. Both sediment and sedimentary porewaters were extracted from these sites and are currently being analysed in various laboratories.

(4) Depending on location, sediment cores ranging from five to 25 metres in length were sampled using either a piston, gravity or box corer.

(5) The uppermost 500 metres of the water column were sampled for plankton using a multi-net and/or a single plankton net.

(6) In individual focus areas (Prydz Bay and off Denman Glacier), an extensive water programme was carried out to characterise the water mass distribution and its physico-chemical properties with regard to the inflow of modified Circumpolar Deep Water.

(7) Various biological culturing studies were conducted on board during the cruise. These put the chemical-oceanographic observations of the cruise in context with the primary productivity in the working area.

(8) Extensive land geological work rounded off the scientific programme.

During a three week field camp period of the land geologists (see below) the remaining scientists onboard RV Polarstern carried out an unexpectedly extensive station programme in various parts of Prydz Bay. We carried out extensive bathymetric mapping at several stations in Prydz Bay to identify the best sediment coring stations and to resolve glacial-morphological structures of the seafloor. This allowed us to map the positions of past Antarctic Ice Sheet grounding zones on the seafloor, which will help to decipher the post-glacial ice retreat history. Sediments sampled via gravity coring in proximity to identified grounding zone wedges will be used to precisely date the regional ice sheet retreat dynamics. Analyses of piston sediment cores up to 22 metres in length from deep channels and depressions with increased sedimentation rates along the ice shelf front will provide details of the post-glacial history of Prydz Bay at unprecedented temporal resolution. On the whole, the water and geology programme in Prydz Bay was very productive, and such a detailed survey of the current water mass distribution has not been carried out for a long time; never before during a Polarstern expedition.

Following the recovery of the land geology team, the cruise continued east along the East Antarctic margin to the Shackleton Ice Shelf and Denman Glacier, where we again carried out an intensive water programme. In this area of the East Antarctic shelf, modified Circumpolar Deep Water flows onto the Antarctic shelf, which leads to considerable basal melting rates of the local ice shelf. After departure from the Antarctic shelf, we realised a unique transect along ~100–105°E, extending from the Antarctic shelf to 45°S, with a total of twelve coupled water

and sediment stations. The results of this work section are another scientific highlight of this EASI-2 cruise. While the water programme was largely completed once the south-north section was finished, several marine geology stations were still visited afterwards. Several long sediment cores were also successfully obtained there, even though the last core locations had to be cancelled due to poor weather conditions.

Scientific highlights of the land campaign

The land geology team was flown out from RV Polarstern near the Australian research station “Davis Station” in eastern Prydz Bay. The geological and geodetic investigations in the Vestfold Hills, an ice-free coastal area on the eastern edge of Prydz Bay, focused on the southern part of this so-called “oasis”. The land group consisted of six people as well as extensive field technology and consumables with a total weight of approx. 3600 kg. The participants and equipment were flown from Polarstern to Watts Hut, a refuge of the Australian Antarctic Division (AAD). A field camp with sleeping tents was set up and operated there using the hut’s infrastructure.

An approximately 13.2 m long sediment core was recovered from the lake ice cover from Watts Lake, a 35 m deep lake directly south of Watts Hut, consisting of 14 overlapping gravity and piston cores. Overlapping gravity and piston cores were obtained at nearby Ellis Fjord at four locations. Three of the locations lie in basins between 110 and 85 m water depth and form an approximately 7.5 km long east-west transect across the southern part of the oasis. At these stations, sediment depths of between 12.6 and 8.0 m were reached. At a fourth station in a lagoon on the north bank of Ellis Fjord, two gravity cores and two piston cores were drilled, reaching a sediment depth of approximately 6.0 m. In parallel with the drilling, a series of onshore measurements and sampling were carried out intermittently throughout the duration of the field campaign. These studies focused on uplifted beach ridges, which were surveyed for morphology using lidar and geodetic methods, examined for internal structure using ground penetrating radar and prospecting, and sampled for luminescence and radiocarbon dating. In addition, marine and lacustrine sediments were sampled in the Watts Lake catchment area. The sample points were partly measured using geodetic methods, as were the current water levels of Watts Lake and Ellis Fjord as well as the morphology of potential flood areas between the water bodies. In addition, soil crusts were obtained for biodiversity studies at three locations.

In parallel and following the work in the Vestfold Hills, other areas of the country were visited by helicopter for a few hours. A geodetic reference station was set up at Gaußberg, glacial gravel was taken for exposure dating and the possibilities for a field camp on the PS141 expedition were explored. An Australian geodetic

reference station was maintained on Gillis Island. Sediment-bearing continental ice was collected during a total of five helicopter-based field campaigns. The first three flights focused on rock outcrops bordering Prydz Bay to the south. During the third flight, a shear moraine was sampled in the eastern Vestfold Hills, during the last flight, sediment-bearing inland ice was sampled on the eastern edge of the Bunger Hills (ca. 101° E).

Scientific Output

List of Publications

Publications are currently being prepared and are not published yet. The bathymetric data are already included in the GEBCO database and was contributed to the Nippon Foundation – GEBCO Seabed 2030 project and incorporated into the latest GEBCO_2025 Grid (GEBCO Bathymetric Compilation Group, 2025). This integration supports the international effort to map the entire global seabed by 2030.

Data

Physical oceanographic data are soon to be published on the Pangaea website.

Cruise Report

PS140: https://doi.org/10.57738/BzPM_0790_2024

SO290

Paleoceanography and chemical oceanography of the southern Tasman Sea

Authors

Institute for Chemistry and Biology of the Marine Environment (ICBM), Carl von Ossietzky University Oldenburg | Oldenburg, Germany

K. Pahnke, C. Ehlert, T. Struve, M. Zander, J. Warnatz, T. Badewien

Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) | Bremerhaven, Germany

F. Lamy, L. Lembke-Jene, N. Ruggieri, C. Gebhardt, M. van der Does, J. Hagemann, V. Wall

Leibniz Institute for Baltic Sea Research Warnemünde (IOW) | Warnemünde, Germany

H. W. Arz, J. Kaiser, H. Krüger, A. Wegwerth

Helmholtz Centre for Geosciences (GFZ) | Potsdam, Germany

N. Nowaczyk

The southeastern Tasman Sea extends from mid to high southern latitudes in the South Pacific, where Antarctic intermediate and bottom water masses are formed and advected northward with significance for the global ocean and climate system. The Tasman Sea is further marked by extended submarine plateaus reaching into different depths in the overlying water column, and by the bordering North and South Islands of New Zealand. SONNE cruise SO290 sampled both the water and sediment columns along a meridional transect with additional proximal to distal transects extending east from New Zealand in order to i) study the chemical signature of Southern Ocean water masses and their potential modifications along their advection paths, ii) contrast changes in marine and continental climate evolution over glacial-interglacial changes of the Late Quaternary, and iii) evaluate the geochemical source signature of Australian dust exported to the South Pacific.

Chemical Oceanography

The dissolved radiogenic neodymium isotope signature ($^{143}\text{Nd}/^{144}\text{Nd}$, expressed in ϵNd) of water masses is largely a function of water mass source region, with additional modifications along water mass circulation pathways through exchange with bottom and margin sediments. Incorporation of seawater ϵNd signatures into authigenic marine sediment archives therefore allows reconstructions of past circulation changes if potential modifications are understood. The distribution of dissolved ϵNd in the southeastern Tasman Sea (selected stations of SO290) largely traces the different water masses (Figure 1). These include Southern Ocean-derived Subantarctic Mode and Antarctic Intermediate Water (SAMW, AAIW) and Lower Circumpolar Deep Water (LCDW) with signatures between -8.8 to -7, as well as North Pacific-derived Pacific Deep Water (PDW) with a signature of -4.7 to -4.2 at the northernmost station on Lord Howe Rise. Our data further show evidence for a unique dissolved rare earth element (REE) signature of Upper Circumpolar Deep Water (UCDW), that allows differentiation from LCDW, which is not possible based on ϵNd in the southern part of the transect (see also Pahnke et al., 2025). Clearly visible along the northern transect is the inflow of AAIW from the Coral Sea north of the Tasman Sea, that is derived from the southeast Pacific and modified particularly through contact with volcanic island margins in the tropical and subtropical region (Behrens et al., 2018; Pham et al., 2019). Quantitative water mass contributions, estimated using Optimum Multi-Parameter Analysis (OMPA), confirm the largely conservative behavior of ϵNd in the study area, suggesting that exchange with bottom or margin sediments do not alter the water mass ϵNd signals along the studied transect despite the vicinity of New Zealand.

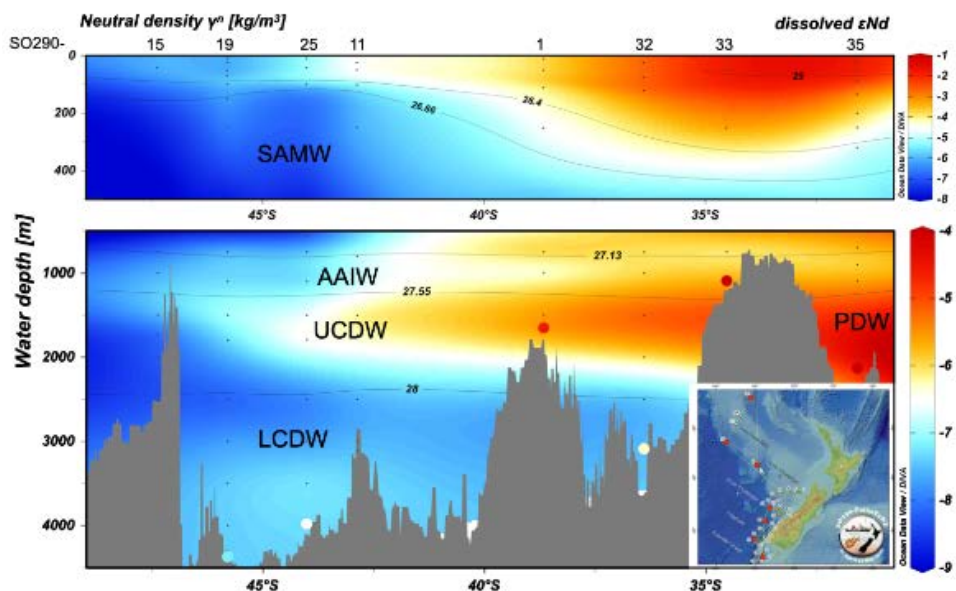


Figure 1: Meridional section along selected stations of cruise SO290 (stations marked by red circles on the inset map) showing the distribution of dissolved ϵNd (colors), neutral density (contours) and the authigenic ϵNd extracted from surface sediments (colored dots) using chemical leaching methods. The sediment ϵNd was measured on single samples (SO290-19, -25, 35) or represents the average of 3-4 individual sample measurements (SO290-01, -08, -32, -33). Figure generated using Ocean Data View (Schlitzer, 2025).

The water column results are reassuring for the use of Nd isotopes for the reconstruction of past ocean circulation in the Tasman Sea. However, even though the trend of the authigenic ϵNd of surface sediments is similar to that of the overlying seawater, the absolute values are offset to more radiogenic ϵNd compared to seawater (colored dots in Figure 1).

Dust provenance

Mineral dust represents an important source of nutrients to the surface ocean. Particularly micronutrients, such as iron (Fe), are supplied to remote ocean areas via dust input and can contribute significantly to phytoplankton growth in areas limited by Fe, such as the Southern Ocean (e. g., Martin et al., 1990). Since Fe-bioavailability depends on the dust properties that vary with dust source region (Shoenfeldt et al., 2018), understanding of primary production and dust dynamics both in the present and past ocean require knowledge of the dust provenance. Since Australia, the currently largest dust source area for the South Pacific (e. g., Prospero et al., 2002; Wengler et al., 2019), harbors several dust source regions, detailed characterization of the geochemical signatures of the dust exported to the South Pacific is crucial. Lord Howe Rise in the northern part of our study area

is ideally located for this purpose due to its bathymetric separation from direct (e. g., river) input from New Zealand and Australia.

Radiogenic Nd, strontium (Sr) and lead (Pb) isotope results measured on the lithogenic <5 µm dust fraction of core SO290-33-2 over the past 140 ka BP indicate mixing of two distinct dust sources (Warnatz, 2024; see also poster by Warnatz et al., this volume). One of these sources can be clearly identified as Lake Eyre Basin with potentially small contributions from Darling Basin based on available literature data. This is consistent with previous results from Holocene sediments of the remote South Pacific, that identified the Lake Eyre and Darling Basins as major dust source areas (Struve et al., 2020; Wengler et al., 2019). Based on currently available geochemical data from potential dust source areas in Australia, the second source cannot be unequivocally identified. A contribution from southern Australia is possible, and temporal variations between the sources over the past 140 ka may be related to changes in the Indo-Australian summer monsoon. The results provide an important basis for the characterization of dust provenance in the South Pacific and their fluctuations in the course of past climate variations.

Calibration of X-Ray Fluorescence (XRF) scans of the sediment cores by discrete geochemical bulk sediment analyses suggest increased dust contributions during glacial times (Lorenzana, 2025), consistent with previous results (Lamy et al., 2014).

Biomarker studies

We investigated biomarker-based sea surface temperature (SST) proxies and terrigenous n-alkane concentrations in surface sediments and downcore. Major results include a seasonal bias of Alkenone paleotemperatures, primarily representing austral summer. Downcore, we focused on core SO290-33 from the Lord Howe Rise, covering the past ca. 580 ka. Alkenone SSTs show strong glacial-interglacial cycles with amplitudes in the range of ca. 5–6°C. Consistent with the dust provenance and bulk sediment analyses, higher glacial n-alkane supply is attributed to dust input from Australia (see Ruggieri et al., and Lamy et al., this volume).

Continental climate

We investigated sediment cores from the Solander Trough south of New Zealand, which represents a major conduit of terrestrial sediments from the Southern Alps. Based on radiocarbon dating, oxygen isotopes, and paleomagnetism we reconstructed 200 ka of glacier dynamics. Terrigenous XRF-based element ratios as well as radiogenic Nd isotopes indicate enhanced terrestrial input variability

during MIS 2, MIS 4 and MIS 6 linked to glacier-induced source changes between the Fiordland and East Southland regions (see Krüger et al., this volume).

References

Behrens MK, Pahnke K, Schnetger B & Brumsack H-J, Sources and processes affecting the distribution of dissolved Nd isotopes and concentrations in the West Pacific, *Geochimica et Cosmochimica Acta* 2018, 222, 508–534, doi:10.1016/j.gca.2017.11.008.

Lamy F, Gersonde R, Winckler G, Esper O, Jaeschke A, Kuhn G, Ullermann J, Martinez-Garcia A, Lambert F & Kilian R, Increased Dust Deposition in the Pacific Southern Ocean During Glacial Periods, *Science* 2014, 343, 403–407, doi:10.1126/science.1245424.

Lorenzana S, Lithogenic input and primary productivity in the eastern Tasman Sea over the last glacial cycle, BSc thesis 2025, Carl von Ossietzky Universität Oldenburg.

Pahnke K, Gutensohn M & Waltemathe H, Upwelling of distinct rare earth element signal in the South Pacific, Goldschmidt Conference, Prague, 2025, 31079.

Pham VQ, Grenier M, Cravatte S, Michael S, Jacquet S, Belhadj M, Nachez Y, Germineaud C & Jeandel C, Dissolved rare earth elements distribution in the Solomon Sea, *Chemical Geology* 2019, 524, 11–36, doi:10.1016/j.chemgeo.2019.05.012.

Prospero JM, Ginoux P, Torres O, Nicholson SE & Gill TE, Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, *Reviews of Geophysics* 2002, 40, 1002, doi:10.1029/2000RG000095.

Shoenfelt EM, Winckler G, Lamy F, Anderson RF & Bostick BC, Highly bioavailable dust-borne iron delivered to the Southern Ocean during glacial periods, *Proceedings of the National Academy of Sciences*, 2018, 115, 11180, doi:10.1073/pnas.1809755115.

Schlitzer R, Ocean Data View, <https://odv.awi.de> 2025.

Struve T, Pahnke K, Lamy F, Wengler M, Böning P & Winckler G, A circumpolar dust conveyor in the glacial Southern Ocean, *Nature Communications* 2020, 11, 5655, doi:10.1038/s41467-020-18858-y.

Waltemathe H, Struve T, Rehbein M & Pahnke K, Influence of water mass mixing and hydrothermal processes on the distribution of dissolved Nd isotopes and concentrations in the South Pacific, *Earth and Planetary Science Letters* 2024, 642, 118846, doi:10.1016/j.epsl.2024.118846.

Warnatz J, Dust provenance in the Tasman Sea during the past 140,000 years, 2024, MSc thesis, Carl von Ossietzky Universität Oldenburg.

Wengler M, Lamy F, Struve T, Borunda A, Böning P, Geibert W, Kuhn G, Pahnke K, Roberts J, Tiedemann R & Winckler G, A geochemical approach to reconstruct modern dust fluxes and sources to the South Pacific, *Geochimica et Cosmochimica Acta* 2019, 264, 205–223, doi:10.1016/j.gca.2019.08.024.

Scientific Output

List of conference presentations

2023 | **Tracing ocean circulation using neodymium isotopes – promises and limitations** EGU General Assembly, Vienna, Austria.

2023 | **Dissolved neodymium isotopes in the Tasman Sea – impact of water mass mixing and non-conservative modifications** IcyMare, Oldenburg, Germany.

2024 | **Influence of water mass mixing and non-conservative modifications on dissolved neodymium isotopes in the eastern Tasman Sea** Ocean Sciences Meeting, New Orleans, USA.

2025 | **Land-ocean interaction in southern New Zealand during the past 200 ka** EGU General Assembly 2025, Vienna, Austria.

Data

Physical oceanography (CTD):
<https://doi.org/10.1594/PANGAEA.959701>

Continuous thermosalinograph oceanography:
<https://doi.org/10.1594/PANGAEA.959029>

ADCP:

<https://doi.org/10.1594/PANGAEA.956603>

<https://doi.org/10.1594/PANGAEA.956641>

Hyperspectral underwater light field:

<https://doi.org/10.1594/PANGAEA.965121>

Hyperspectral downward irradiance in air:

<https://doi.org/10.1594/PANGAEA.965132>

Hyperspectral downward irradiance in water:

<https://doi.org/10.1594/PANGAEA.965123>

Hyperspectral upward radiance in water:

<https://doi.org/10.1594/PANGAEA.965134>

Master track of SO290:

<https://doi.org/10.1594/PANGAEA.947864>

Master track of SO290 1s resolution:

<https://doi.org/10.1594/PANGAEA.947863>

Cruise Report

SO290: https://doi.org/10.48433/cr_so290

SO292

ICECARB: Towards an understanding of carbonate platforms in the icehouse world

Authors

University of Hamburg, Department of Earth System Sciences | Hamburg, Germany
T. Lüdmann, S. Lindhorst, C. Betzler, C. Hübscher

Study area and objectives

Many elements of the modern climate and ocean circulation system were emplaced during the Neogene, such as a permanent high-latitude ice sheets influenced by orbital variations (Hays and Imbrie, 1976; Sugden et al., 1993; Lisiecki and Raymo, 2005). Expansion of the East Antarctic ice sheet triggered the development of a steep global meridional temperature gradient, intensifying atmospheric pressure systems and ocean circulations (Flower and Kennett, 1994; Zachos et al., 2001). Betzler and Eberli (2019) discussed that current-controlled became dominant on carbonate platform development at this time of Middle to Late Miocene stepwise global cooling (Holbourn et al., 2013) and the onset of modern ocean circulation. In addition to the emergence of current-controlled sedimentation in and around distinct isolated carbonate platforms, partial carbonate platform drowning occurred at the Maldives at ~13 Ma (Betzler et al., 2016) and at the Marion Plateau at ~13.6 Ma (John and Mutti, 2005), which coincides with this oceanographic change. The late Middle Miocene was therefore seen as a major break in global carbonate platform evolution (Betzler and Eberli, 2019).

The East Australian carbonate province which encompasses the Great Barrier Reef, the Marion Plateau and the Queensland Plateau has been in the focus of integrated sedimentological, stratigraphic, and paleoceanographical research including ODP Leg 133, which cored several sites (Davies et al., 1991) as far down as the basement. The ICECARB project focused on the Queensland Plateau, which consists of isolated carbonate banks showing a major turnover of the stratigraphic architecture and facies during the Miocene, which is so far not well understood

(Figure 1). The overarching objective of SO292 was to test the hypotheses that 1.) since the onset of global cooling during the middle to late Miocene, ocean currents have strongly controlled tropical carbonate platforms; 2.) modern carbonate platforms currently exist in an “icehouse world mode”. These objectives were supposed to be addressed through the following aims: 1.) integration of seismic reflection data with stratigraphic information from ODP Leg 133 sites at the Queensland Plateau carbonate platform, to elucidated the processes governing the backstepping of carbonate bank margins; 2.) placing a major focus on the mapping and correlation of bottom- and contour-current-related features, such as submarine dunes, drift sediment bodies, and current moats; 3.) investigating recent and most recent depositional processes occurring on the carbonate banks, using multibeam and Parasound data, with particular emphasis on determining the impact of ocean currents on the carbonate source-to-sink system; 4.) examining sedimentological variations related to carbonate bank exposure to currents and wind through analyses of sediment composition and texture, thereby linking geological and geophysical datasets. In addition, CTD (conductivity–temperature–depth) measurements up- and down-current of the carbonate buildups allow to assess how carbonate banks exposed to ocean currents influence water-mass stratification. Scientific outcomes of the cruise so far, are described in the following. Ongoing research is focused on glacial-interglacial variability of bottom-current activity around the banks.

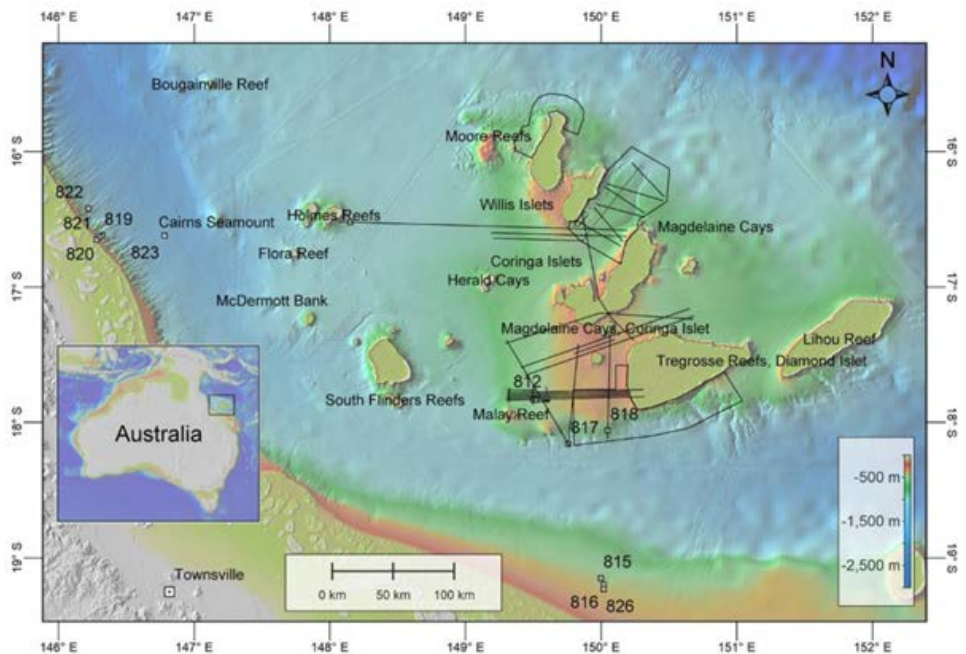


Figure 1: SO292 seismic survey lines and outline of detailed study areas in the central Queensland Plateau (NE Australia).

Seismic stratigraphic and sedimentary record of partial carbonate platform drowning

SO292 data show that the carbonate platforms of the Queensland Plateau underwent a partial drowning between 13.6 and 12.7 Ma. This partial drowning is coeval with the onset of current-driven sedimentation and the termination of the Miocene Climate Optimum. Relict platforms, which form the core of the presently still active platforms, were established in two steps: After the demise of a spatially expanded platform, a system of smaller, low-relief banks and mounds established with a fauna devoid of corals or calcifying green algae. This process lasted from 12.7 to ca. 3.7 Ma (Figure 2, interval PT to MT). At around 3.7 Ma, there was a turnover in platform development and higher relief, flat-topped platforms established (Figure 2, MT to seafloor). During this phase, the bank first aggraded, then, after an episode of margin retrogradation, bank margin progradation started around 1 million years ago (Figure 2, after DSB2). Fundamental changes in the water-mass properties or a rise in sea level are not seen as controlling factors of this evolution. Instead of we propose that the geologic record of the Queensland Plateau represents an excellent example of carbonate platform evolution controlled by ocean currents.

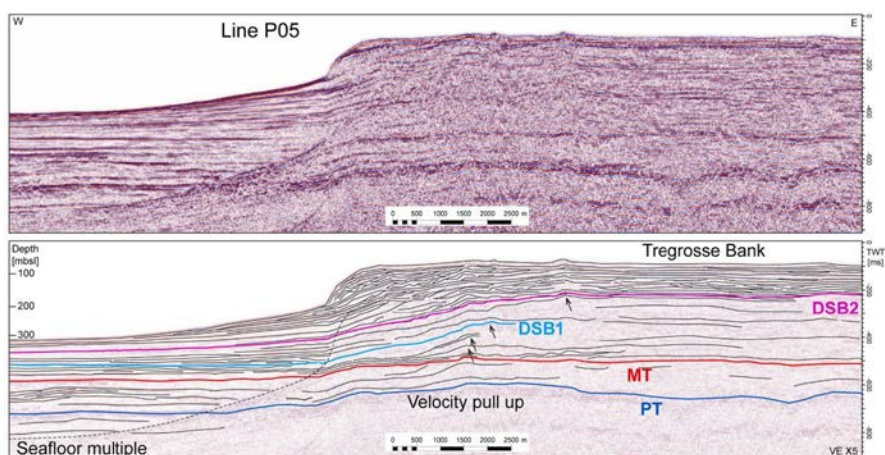


Figure 2: Part of W-E seismic line P05 with detail of the stratigraphy of Tregosse Bank (Betzler et al., 2024b). The mound unit (PT to MT) does not show major lateral variations in thickness. Above the Platform Top horizon (PT), the growth pattern of the bank is first aggradational, changing into a retrogradation at DSB1 before the bank edge started to prograde above DSB2. Dashed line: seafloor multiple. PT = platform top, MT = mound top, DSB = drift sediment boundary.

Carbonate platform dismantling

The steep slopes of carbonate platforms frequently display large-scale sediment destabilization features like rockfalls, mass transport complexes, and slope

erosion. The processes and factors triggering such instabilities and how they interact are a matter of ongoing discussion (Frost & Kerans, 2009; Ginsburg et al., 1991; Mulder et al., 2012; Adams & Kenter, 2014; Wunsch et al., 2017; Etienne et al., 2021). New data from the isolated Tregrosse carbonate bank on the Queensland Plateau (Figure 93) allowed to characterize slope instabilities and their potential controlling factors (Figures 3, 4). Along the flanks of the bank, erosion of gullies and submarine valleys is concentrated in slope segments with the platform rim at several 10s of meters of water depth, i. e. where there is potential for sediment transfer from the bank interior to the slope. Gravity core data indicate that most sediment export from the platform occurs during sea-level fall. The toe of slopes neighboring segments with a shallower platform rim are mostly characterized by mass-transport complexes of platform rim and upper slope rocks forming extended block fields. Distal slope areas are dismantled through submarine landslides, resulting in scalloped head scarps. The basal detachment surface of these submarine landslides appears to be rooted in several 100s of meters in the subsurface at a lithological heterogeneity, which is documented by a gamma-ray peak in the downhole logging data from Ocean Drilling Program Site 817. Our findings show that 1.) canyon erosion, 2.) platform rim and upper slope destabilization as well as 3.) lower slope dismantling, largely act independently of each other to destabilize the flanks of the carbonate bank.

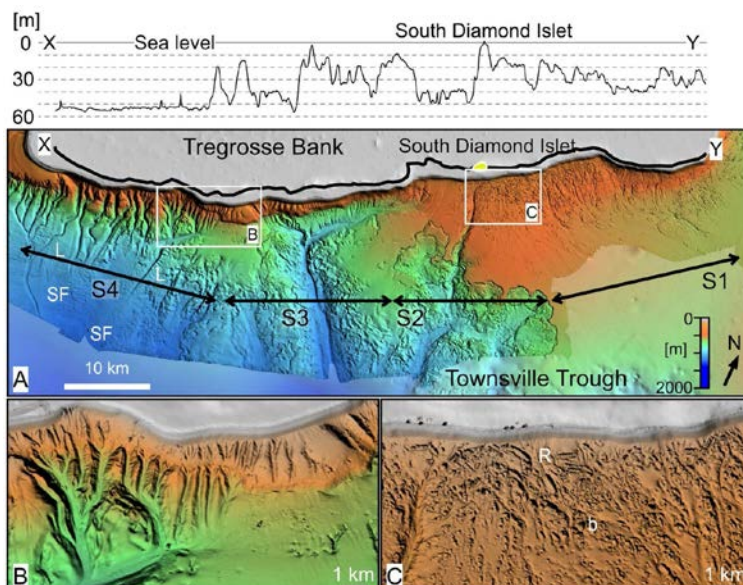


Figure 3: A: Sea-floor morphology along the southern flank of Tregrosse Bank (Betzler et al., 2024a). The black line (X-Y) along the bank margin indicates the position of the section along the highest elevations in the platform rim area (top). The differences in the sea-floor morphology and features south of the bank allow the subdivision of the slope into four segments (S1-S4). White rectangles mark the extension of detail views in the lower part of the figure. L: channel levee; SE: scalloped edge; SF: submarine fan. B, C: Detailed map views of corresponding areas shown in A. Bb: block; R: ridge.

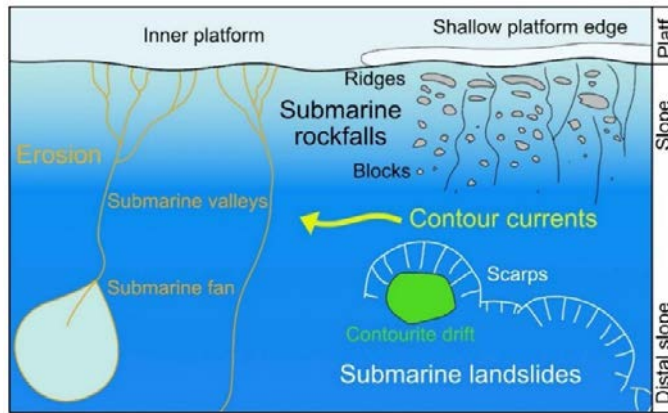


Figure 4: Main processes and products of the dismantling of the southern flank of Tregosse Bank (Betzler et al., 2024a). Figure is not to scale.

Detached low-gradient deep-water channels

Sediment conduits like erosive canyons and channels are common morphological elements of submarine landscapes down to abyssal depths. While canyon-channel systems connected to slopes and shallow water are well studied, detached sediment-routing systems emerging in deeper waters have received less attention, especially in carbonate settings. In the frame of SO292, we studied the sedimentary architecture and evolution of an extensive canyon-channel system in the 'Willis Passage', a marine strait between the Magdelaine and Willis carbonate banks (Queensland Plateau, northeast Australia) (Lindhorst et al., in press). The canyon-channel system is detached from the slopes of the carbonate banks, emerges at depths of >500 m and runs over more than 100 km towards the slope break of the carbonate plateau (Figure 5). The canyon is several kilometres wide and several tens of meters deep. Morphological edges (knickpoints) occur along the canyon course, one with a plunge pool at its downstream foot wall. Current ripples and coarse-grained lag deposits at the floor of the canyon indicate bottom-current activity and possibly winnowing of fine-grained sediment. The seafloor outside the canyon is intersected by bundles of grooves (linear seafloor cuts), tens of kilometers long. Sedimentological and morphological characteristics indicate that canyon-channel system and grooves are shaped by eastward-flowing bottom currents, which is in a direction counter to the dominant westward-flowing oceanic current regime. Based on new geophysical and oceanographic data, as well as video observations of the seafloor, we propose that eastward-flowing sediment-laden bottom currents originate from the channelization of oceanic currents by the carbonate edifices of the Queensland Plateau, paired with tidal pumping in the narrow passages between the banks. This mechanism is most efficient during episodes of lowered sea level, while bottom currents are much weaker during sea-level highstand. New seismic data reveal the existence of buried individual canyon-channel systems and document that the Queensland Plateau underwent episodic changes in the local current regime since the upper

Miocene. We propose that slope-detached deep-water canyon-channel systems act as a conveyor, routing sediment from carbonate platforms to the deep ocean. As a link between the neritic realm and abyssal depths, these systems are important agents of dismantling and degradation of carbonate platforms and underline the role of bottom currents in shaping these depositional environments.

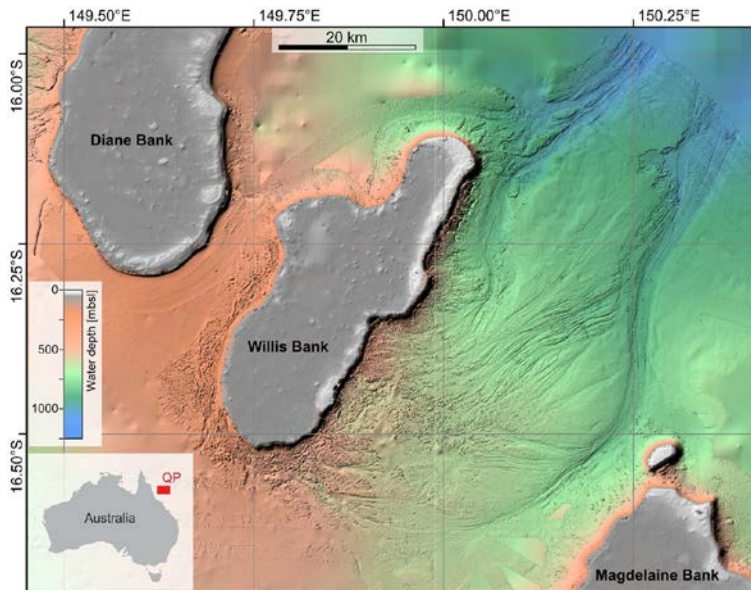


Figure 5: Multibeam bathymetry of the surroundings of Willis Bank and the marine Passage between Willis and Magdelaine banks with north-east trending deep-water canyon-channel systems (Lindhorst et al., in press).

A new type of Halimeda bioherms

Halimeda bioherms are described from Holocene marine deposits all over the world, including the Nicaraguan Caribbean Sea (Hine et al., 1988), the Java Sea (Phipps and Roberts 1988), and most notably in the Great Barrier Reef (Orme et al. 1978; Orme & Salama 1988). In the Great Barrier Reef (GBR), Halimeda bioherms are larger in size than anywhere else and often associated with an extensive sheet-like form, described as biostromes (Orme & Salama 1988), and surfaces covered by Halimeda meadows (Drew & Abel 1988; Wienberg et al., 2010). On the Queensland Plateau, Halimeda buildups consist of cone-like mounds up to 500 m in diameter and 3–10 m high, with gentle slopes (Reolid et al., 2024). Bioherms occur in water depths of 10–70 m, with most bioherm between 50 and 65 m. Their internal structure consists of aggrading low-amplitude reflections at the core of the bioherm interfingering with high-amplitude reflections to the flanks. Surface facies distribution displays one to four facies belts, from distal to proximal: Halimeda rudstone, Halimeda rudstone with living plants, Halimeda rudstone with coralgall debris, and coralgall boundstone (when present, occupied the top of the

bioherms). SO292 data allow to propose that the alternation of two key processes contributes to the formation of these bioherms: 1.) in situ accumulation of *Halimeda* debris and 2.) episodic dismantling of the mesophotic corallgal boundstone at the centre of the bioherm by severe storms. These storms may dismantle the mesophotic reef and export corallgal rubble to the flanks. Flanks may be recolonized by *Halimeda* during fair-weather periods. Due to their different geomorphic expressions, complex internal structure, and surficial facies distribution, we suggest that the buildups of the Queensland Plateau represent a new *Halimeda* bioherm morphotype, distinct from previously described bioherms on the adjacent Great Barrier Reef and elsewhere globally (Reolid et al., 2024).

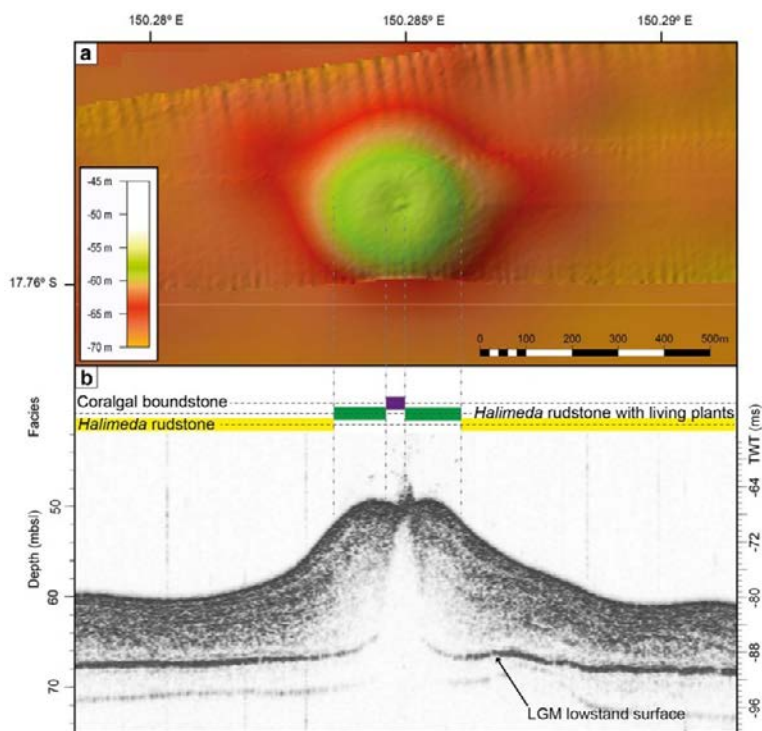


Figure 6: *Halimeda* mound on the Tregrosse carbonate platform. a: Multibeam bathymetry map. B: Parasound profile with surface facies distribution. LGM, last glacial maximum (Reolid et al., 2024).

References

Adams EW & Kenter JAM, So different, yet so similar: Comparing and contrasting siliciclastic and carbonate slopes. In: Verwer K, Playton TE, Harris, PM (Eds.), Deposits, Architecture, and Controls of Carbonate Margin, Slope and Basinal Settings, SEPM Special Publication, SEPM Society for Sedimentary Geology 2014, Tulsa, pp. 14–25. doi.org/10.2110/sepm.sp.105.14.

Beaman RJ, High-resolution depth model for the Great Barrier Reef and Coral Sea – 100 m, Geoscience Australia 2010, Canberra, doi.org/10.26186/5e2f8bb629d07.

Beaman R, Schmidt Ocean Institute, 2024, Schmidt Ocean Institute Expedition Report: Visioning the Coral Sea Marine Park, Zenodo, pp. 39, doi.org/10.5281/zenodo.14335264.

Betzler C & Eberli GP, Miocene start of modern carbonate platforms, *Geology* 2019, 47, 771–775.

Betzler C, Hübscher C, Lindhorst S, Lüdmann T, Reijmer JJG & Braga J-C, Lowstand wedges in carbonate platform slopes (Quaternary, Maldives, Indian Ocean), *Depositional Rec.* 2016, 2, 196–207.

Brooke B, 2020 Marine Geoscience Data System, Cruise RV Falkor FK200802 www.marine-geo.org/tools/search/entry.php?id=FK200802.

Davies PJ, McKenzie JA, Palmer-Julson A, et al., *Proc. Ocean Drill. Proj., Init. Repts* 1991, p. 133.

Drew EA & Abel KM, *Studies on Halimeda. Coral Reefs* 1988, 6, 195–205.

Flower BP & Kennett JP, The middle Miocene climatic transition: East Antarctic ice sheet development, deep ocean circulation and global carbon cycling, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 1994, 108, 537–555.

Frost EL & Kerans C, Platform-margin Trajectory as a Control on Syndepositional Fracture patterns, Canning Basin, Western Australia, *J. Sediment. Res.* 2009, 79, 44–55. doi.org/10.2110/jsr.2009.014.

Ginsburg RN, Harris PM, Eberli GP & Swart PK, The growth potential of a bypass margin, Great Bahama Bank, *J. Sediment. Petrol.* 1991, 61, 976–987, doi.org/10.1306/D426781B-2B26-11D7-8648000102C1865D.

Hays JD, Imbrie J & Shackleton NJ, Variations in the earth's orbit: pacemaker of the ice ages, *Science* 1976, 194, 1121–1132.

Hine AC, Hallock P, Harris MW, Mullins HT, Belknap DF & Jaap WC, Halimeda bioherms along an open seaway: Miskito Channel, Nicaraguan Rise, SW Caribbean Sea, *Coral Reefs* 1988, 6, 173–178.

Holbourn A, Kuhnt W, Clemens S, Prell W & Andersen N, Middle to late Miocene stepwise climate cooling: evidence from a high-resolution deep water isotope curve spanning 8 million years, *Paleoceanography* 2013, 28, 688–699.

John CM & Mutti M, Relative Control of Paleoceanography, climate, and Eustasy over Heterozoan Carbonates: a Perspective from Slope Sediments of the Marion Plateau (ODP LEG 194), *J. Sediment. Res.* 2005, 75, 216–230.

Lisiecki LE & Raymo ME, A Pliocene-Pleistocene stack of 57 globally distributed benthic D18O records, *Paleoceanography* 2005, 20, PA 1003.
doi.org/10.1029/2004PA001071.

Mulder T, Ducassou E, Eberli GP, Hanquiez V, Gonthier E, Kindler P, Principaud M, Fournier F, Leonide P, Billeaud I, Marsset B, Reijmer JJG, Bondu C, Joussiaume R & Pakiades M, New insights into the morphology and sedimentary processes along the western slope of Great Bahama Bank, *Geology* 2012, 40, 603–606,
doi.org/10.1130/G32972.1.

Orme GR & Salama MS, Form and seismic stratigraphy of Halimeda banks in part of the northern Great Barrier Reef Province, *Coral Reefs* 1988, 6, 131–137.

Orme GR, Flood PG & Sargent GEG, Sedimentation trends in the lee of outer (ribbon) reefs, Northern Region of the Great Barrier Reef Province, *Philos Trans R Soc London Ser a, Math Phys Sci* 1978, 291, 85–99.

Phipps CVG & Roberts HH, Seismic characteristics and accretion history of Halimeda bioherms on Kalukalukuang Bank, eastern Java Sea (Indonesia), *Coral Reefs* 1988, 6, 149–159.

Sugden DE, Marchant DR & Denton GH, The Case for a Stable East Antarctic Ice Sheet: the Background. *Geografiska Annaler Series A, Physical Geography* 1993, 75, 151–154.

Wienberg C, Westphal H, Kwohl E & Hebbeln D, An isolated carbonate knoll in the Timor Sea (Sahul Shelf, NW Australia): facies zonation and sediment composition. *Facies* 2010, 56, 179–193.

Wunsch M, Betzler C, Lindhorst S, Lüdmann T & Eberli GP, Sedimentary dynamics along carbonate slopes (Bahamas archipelago), *Sedimentology* 2017, 64, 631–657.
doi.org/10.1111/sed.12317.

Zachos J, Pagani M, Sloan L, Thomas E & Billups K, Trends, Rhythms, and Aberrations in Global climate 65 Ma to present, *Science* 2001, 292, 686–693.

Scientific Output

List of Publications

Betzler C, Lindhorst S, Hincke C, Eisermann JO, Bialik O, Petrovic A, Reolid J, Beaman RJ, Webster J, Lüdmann T & Hübscher C, Dismantling of an isolated tropical carbonate platform through flank collapse and canyon erosion, Coral Sea, northeast Australia, *Marine Geology* 2024a, 475, doi:10.1016/j.margeo.2024.107361 (open access).

Reolid J, Bialik OM, Lindhorst S, Eisermann JO, Petrovic A, Hincke C, Beaman RJ, Webster JM & Betzler C, A new type of Halimeda bioherm on the Queensland Plateau, NE Australia, *Coral reefs* 2024, 43, 801-821, doi:10.1007/s00338-024-02500-0 (open access).

Betzler C, Hübscher C, Lindhorst S, Lüdmann T, Hincke C, Beaman RJ & Webster JM, Seismic stratigraphic and sedimentary record of a partial carbonate platform drowning, Queensland Plateau, north-east Australia, *Marine Geology* 2024b, 470, 107255. doi:10.1016/j.margeo.2024.107255 (open access).

Lindhorst S, Budke L, Beaman RJ, Eisermann JO, Hübscher C, Lahajnar N, Lüdmann T, Webster JM & Betzler C, Deep-water canyon-channel systems of the Queensland Plateau, northeast Australia. *Marine Geology*, submitted, minor revision.

List of conference presentations

2023 | **Erosive channels in deep-water areas surrounding carbonate banks of the Queensland Plateau (NE Australia).** 36th Meeting of the International Association of Sedimentologists (IAS), Dubrovnik, Croatia.

2023 | **A new type of mesophotic Halimeda bioherm (Queensland Plateau, NE Australia).** 36th Meeting of the International Association of Sedimentologists (IAS), Dubrovnik, Croatia.

2023 | **Disintegration of Isolated Tropical Carbonate Platforms through Flank Collapse and Canyon Erosion.** 36th Meeting of the International Association of Sedimentologists (IAS), Dubrovnik, Croatia.

2025 | **Detached low-gradient deep-water channels of the Queensland Plateau.**
38th Meeting of the International Association of Sedimentologists (IAS), Huelva,
Spain.

Data

Multibeam bathymetry (EM710):
<https://doi.org/10.1594/PANGAEA.965785>

Multibeam bathymetry (EM122):
<https://doi.org/10.1594/PANGAEA.965787>

Water column data (EM710):
<https://doi.org/10.1594/PANGAEA.965786>

Water column data (EM122):
<https://doi.org/10.1594/PANGAEA.965788>

Parasound (PS70):
<https://doi.org/10.1594/PANGAEA.969088>

Thermosalinograph:
<https://doi.org/10.1594/PANGAEA.956431>

Mastertrack:
<https://doi.pangaea.de/10.1594/PANGAEA.948203>

2D multichannel seismic reflection:
<https://doi.org/10.1594/PANGAEA.965100>

CTD data (Yo-Yo):
<https://doi.org/10.1594/PANGAEA.973811>

CTD data:
<https://doi.org/10.1594/PANGAEA.973808>

Cruise Report

SO292: https://doi.org/10.48433/cr_so292

SO292/2

Characterization and monitoring of serpentinite mud volcanoes' fluid/solid emissions in the Mariana Forearc

Authors

Center for Marine Environmental Sciences MARUM, University Bremen | Bremen, Germany

W. Menapace, A. Kopf
and the SO292/2 Scientists

Subduction zones represent some of the most dynamic environments on Earth, controlling mass and energy fluxes between the surface, crust, and mantle. Among their most striking expressions are serpentinite mud volcanoes (SMVs), unique geological structures that recycle subducted sediments and hydrated mantle materials back to the seafloor. The DeepBlue project (SO292/2, R/V Sonne) focused on characterizing fluid and solid emissions from SMVs in the Mariana forearc and deploying novel in situ observatories for long-term monitoring.

During the expedition (June–July 2022), five serpentinite mud volcanoes at different distances from the trench were sampled by coring, dredging, and remotely operated instrumentation. Three previously unknown mud volcanoes were discovered (Layuliyar Araw Hill, Subetbia, and Haga' I Tasi, named in the Chamorro language). Haga' I Tasi represents the deepest mud volcano ever discovered, with a summit depth of ~5930 m. Additionally, a potentially new serpentinite-hosted hydrothermal field was identified. These discoveries significantly expand our understanding of forearc structures and their role in mass recycling in subduction settings.

Collected samples included sediments, rocks, pore waters, gases, and authigenic carbonates. Initial geochemical analyses of pore waters indicate that most SMVs do not exhibit evidence for continuous fluid discharge, although fluid–rock interactions remain pervasive. Only a few sites show active fluid transport pathways from the subducting crust to the surface. Notably, no methane was detected in pore waters, despite lipid biomarker evidence for methanogenic archaea dominating the serpentinite-rich sediments. This microbial signature resembles the communities described at the Lost City hydrothermal field, implying comparable chemosynthetic ecosystems sustained by serpentinization-derived energy sources.

Rock dredging revealed unprecedented lithological successions from the Mariana forearc, including boninites and fractionated plutonic rocks (gabbro-norite, norite, orthopyroxenite, cumulate harzburgite, dunite, and residual harzburgite). These findings provide the first direct evidence of consecutive mafic-ultramafic lithologies derived from the lower crust and Moho transition zone in this setting. The presence of boninitic magmatism suggests that forearc crust formation began shortly after subduction initiation and that serpentinization processes may extend to the Moho.

Sediment analyses identified event beds from sediment-gravity flows (SGFs) in isolated basins, documenting extreme depositional events linked to slope failures, earthquakes, or mud volcanic activity. High-resolution micro-CT imaging highlighted internal sedimentary structures not visible macroscopically, offering novel insights into the dynamics of forearc mass transport.

Mineralogical and isotopic characterization of authigenic carbonates (aragonite with iron oxide inclusions) demonstrated precipitation from seawater-fluid reactions, constraining natural mineral carbonation processes. These findings are highly relevant for carbon dioxide removal (CDR) and carbon capture and storage (CCS) strategies, as they provide natural analogues for mineral trapping of CO₂.

Geomicrobiological studies revealed distinct microbial communities in serpentinite muds compared to overlying pelagic sediments. Lipid biomarker profiles indicate dominance of methanogenic archaea and bacteria producing ether-bound membrane lipids—adaptations consistent with energy-limited, high-pH environments. These results support the hypothesis that the hydrated mantle wedge beneath the Mariana forearc may host one of Earth's largest hidden microbial ecosystems.

Porosity and fluid analyses confirmed heterogeneous fluid circulation, with Sr isotopic signatures documenting contributions from altered oceanic crust. Installation of long-term pressure-temperature observatories at key SMVs will, over the coming years, provide critical time-series data on episodic fluid emissions and their relation to seismic and tectonic processes.

Beyond scientific breakthroughs, DeepBlue emphasized education and outreach. New SMVs were named in collaboration with the indigenous Chamorro community of the Mariana Islands and approved by UNESCO's Intergovernmental Oceanographic Commission. Project results were integrated into MARUM's school laboratory programs, enabling hands-on learning for students from primary to secondary levels. Public engagement included podcasts, media articles, and lectures, broadening societal awareness of deep-sea science and its relevance to planetary processes.

In synthesis, DeepBlue has advanced our understanding of forearc dynamics, serpentinite mud volcanism, and their geomicrobiological significance. Key outcomes include:

- Discovery of new serpentinite mud volcanoes, including the world's deepest.
- First recovery of complete lithological sequences from the lower crust/Moho in the Mariana forearc.
- Identification of authigenic carbonates as natural analogues for mineral carbonation and CO₂ sequestration.
- Evidence for methanogenic and extremophilic microbial ecosystems thriving in energy-limited serpentinite muds.
- Deployment of long-term observatories for fluid and pressure monitoring.

We therefore propose that: (i) the hydrated mantle wedge beneath the Mariana forearc constitutes one of Earth's largest cryptic microbial habitats; (ii) serpentinitization and boninite formation extend to the outer forearc, beginning soon after subduction initiation; and (iii) sediment-gravity flows in isolated basins serve as archives of extreme events shaping convergent margins.

The outcomes of DeepBlue are highly relevant not only for subduction zone geodynamics, but also for life at extreme depths, the deep carbon cycle, and global efforts to understand natural analogues for carbon capture. Future work (DeepBlue II) will recover the installed observatories, enabling temporal resolution of fluid dynamics and their coupling to tectonic events. Through interdisciplinary collaboration across Europe, the U.S., and Asia, DeepBlue demonstrates the power of integrating geology, geochemistry, microbiology, and technology to illuminate hidden Earth processes at one of the planet's most extreme convergent margins.

Scientific Output

List of Publications

Kumawat P, Albers E, Bach W, Klein F, Menapace W, Vogt C & Schubotz F, Biomarker evidence of a serpentinite chemosynthetic biosphere at the Mariana forearc, *Communications Earth & Environment* 2025, 6(1), 659.

Menapace W & Kopf A, Marianengraben - Am Puls der tiefen Erde. In: *Geowissenschaftliche Mitteilungen – GMIT*, 2023, 92, ARGE GMIT, Bonn, 124 S., doi.org/10.23689/fidgeo-5790.

List of conference presentations

2025 | **Chemosynthetic Life Beyond Hydrothermal Vents: Exploring the Lipidome of the Serpentinite Biosphere** Goldschmidt, Prague, Czech Republic.

2025 | **Petrology of a rock suite of the Moho transition zone beneath the Mariana forearc: Interaction between the mantle and boninitic melts** JpGU Meeting, Chiba, Japan.

2025 | **Mariana Trench Serpentinite Mud Volcanoes: Geochemical, Mineralogical and Biomarker Analogs for Mars and Ocean Worlds** International Clay Conference, Dublin, Ireland

2023 | **First MAX- DOAS results of the SO292-2 cruise across the Pacific in June/ July 2022: Nouméa (New-Caledonia) to Dutch Harbor (Alaska, USA)** EGU, Vienna, Austria

2022 | **Serpentinite mud volcanism in the Mariana forearc: current studies and new perspectives** SCYLLA – Magellan Workshop, Bologna, Italy.

Data

ADCP:

<https://doi.org/10.1594/PANGAEA.957035>

<https://doi.org/10.1594/PANGAEA.957030>

Thermosalinograph:

<https://doi.org/10.1594/PANGAEA.956369>

Bathymetry:

<https://doi.org/10.1594/PANGAEA.955291>

<https://doi.org/10.1594/PANGAEA.956750>

<https://doi.org/10.1594/PANGAEA.957030>

<https://doi.org/10.1594/PANGAEA.955289>

Cruise Report

SO292/2: https://doi.org/10.48433/cr_so292_2

Authors

**Senckenberg Research Institute and Natural History Museum Frankfurt and
Goethe-University Frankfurt | Frankfurt, Germany**

A. Brandt, S. Brix, D. Di Franco, S. Kaiser, P. Martinez

The aim of the AleutBio project was the systematic assessment of changes in species composition and biogeographical distribution in previously poorly studied deep-sea areas of the North Pacific. Based on new samples collected from the Aleutian Trench (AT), the project sought to identify large-scale biogeographic patterns and compare them with data from earlier expeditions (including KuramBio I & II, SoJaBio, SokhoBio) as well as historical Russian deep-sea surveys. Due to geopolitical restrictions, the original focus had to be shifted from the Kuril-Kamchatka Trench (KKT) and western AT to the eastern AT within the Exclusive Economic Zone (EEZ) of the United States. Nevertheless, the core objectives of the project remained unchanged. Central research questions included the species diversity in hadal habitats, the degree of isolation of species depending on their reproductive strategies, and the role of the Kamchatka Strait as a biogeographical filter or corridor. The project contributes to a better understanding of biodiversity, its distribution, and its responses to climate change in Arctic-Pacific deep-sea ecosystems. Despite the geographic shift to the eastern Aleutian deep-sea region, the AleutBio expedition maintained its original objective of investigating changes in species composition in the North Pacific and the Bering Sea under the influence of climate change. The following hypotheses were tested:

1. The hadal environment of the eastern AT harbors a similarly high species diversity as the KKT.
2. The hadal depths of the eastern AT and the KKT isolate sediment-dwelling and brood-caring species from the Bering Sea, while species with pelagic larval stages may be dispersed by ocean currents.
3. The Kamchatka Strait acts as a migration filter for species moving from the eastern AT into the Bering Sea, while at the same time serving as a corridor for species from the Arctic Ocean and the Bering Sea into the KKT and the open Northwest Pacific.

Taxonomic and Genetic Analyses, and Studies on Biogeographic Connectivity

Organisms extracted from the samples were first identified at higher taxonomic levels (e. g., phylum, class, order). For selected taxa, genetic samples were taken to enable further molecular analyses.

Based on these data, **abundance, diversity, and geographic distribution were assessed for various major taxa and selected species.** Particular attention was given to **investigating the potential barrier function of the AT and its associated depth gradient.** The study aimed to determine the extent to which this trench acts as a dispersal barrier, thereby shaping biogeographic patterns.

Such a barrier effect would be reflected in differences in species composition north and south of the trench, as well as in significant genetic distances between individuals of the same species occurring on either side. Comparable evidence for such differentiation already exists for a species of the isopod families Macrostylidae and Haploniscidae from the Kuril-Kamchatka Trench (KKT) (Bober et al., 2018b; Knauber et al., 2025).

However, the data available from the earlier KuramBio-I expedition were limited. The new data from the AleutBio expedition, supplemented by comparative samples from the KuramBio-II expedition, are now expected to provide a deeper understanding of the role of both the KKT and the AT in shaping the genetic structure and differentiation of benthic organisms.

In addition, **connectivity analyses were conducted across large geographic distances (~3,000 km) between the KKT and the AT.** Further studies focused on the connectivity between the Bering Sea and the AT, as well as between slope and abyssal zones of the northeastern Pacific (Knauber et al., 2025; Ohta et al., in press).

The following **key research questions** were addressed in the context of genetic and biogeographic analyses:

- Which major taxa of benthic macrofauna occur along the AT and in the Bering Sea?
- Which taxa are present both in the abyssal plains and in the hadal trench, as well as in the Bering Sea? Are there significant differences in biodiversity among these zones?

- Which taxa exhibit endemic distributions – i. e., occurrences restricted to specific depth zones or geographic regions?
- To what extent do species compositions in the KKT overlap with those of the northwestern Pacific? How do these results compare with data from earlier German-Russian deep-sea expeditions since 2010 (e. g., KuramBio I & II, SokhoBio)?

Results

The AleutBio expedition provided first insights into north-eastern Pacific deep-sea macrofaunal composition from the Bering Sea and the AT and slope and helped to **improve knowledge of the bathymetry** of the region considerably (Jakobsson et al., 2024). In the AleutBio trench and Bering Sea, we studied meiofaunal (Bonk et al., 2024) and macrofaunal composition (Brandt et al., 2024; Preikschat et al., 2025) and abundance across regions and depths. **The Bering Sea differs from Aleutian slope and trench.** A gap analysis of OBIS and GBIF data revealed that only 153 of 170,627 records from the North Pacific and Bering Sea were from below 3,500 m (Brandt et al., 2024). AleutBio addressed this by adding over 36,499 new deep-sea records via EBS sampling. Nearly 98% of specimens belonged to five phyla – Arthropoda, Annelida, Mollusca, Echinodermata, and Nematoda – with Polychaeta, Copepoda, and Nematoda being most abundant. 6100 specimens of echinoderms from the Bering Sea and the AT (3498 to 7254 m) were examined documenting 39 species belonging to 31 genera including several new putative species (Moreau et al., 2025). The role of the AT as a biogeographic barrier is unlikely for echinoderms and estimations of its richness are higher than previously thought.

While individual counts varied by station, overall abundance did not decline significantly with depth, and some hadal stations matched abyssal ones in numbers. Regionally, Polychaeta and Nematoda dominated in the Bering Sea, while Copepoda were more common in western abyssal sites. **Depth was the main factor shaping distribution, with clear patterns across bathyal, abyssal, and hadal zones within macrofauna in general (Brandt et al., 2024).** At genus and species level of Isopoda, the composition of isopods exhibited significant differences between the abyssal north and south of the AT and the hadal. **Most isopod species identified (~77%) were new to science and only a few were shared between stations or depth horizons. While the abyssal north AT showed the highest species diversity,** the Bering Sea displayed lowest diversity levels possibly due to its high degree of geographic isolation. **Overall, food availability and sediment characteristics appeared to be the main drivers of differences in macrofaunal densities, community composition, and isopod diversity.**

The distribution and composition of meiofaunal organisms were found to be influenced by water depth, silt and clay content, and TOC (Bonk et al., 2025). Comparisons with other NW Pacific regions showed depth and water body isolation as key drivers of faunal structure.

AleutBio's expanded dataset significantly enhances knowledge of NE Pacific deep-sea biodiversity. Though some taxa had patchy distributions, no major differences in faunal composition were found across regions or depth zones. These results highlight the dynamic nature of deep-sea ecosystems and the critical role of depth in structuring macrofaunal communities, underscoring the need for continued research. The **largest munnopsid isopod, *Bathyporus sonnei* Brandt & Kelch, 2025, has been reported and extended the bathymetric distribution to the northern most record of the Bathyporinae in the AT (Brandt et al., 2025).**

Neoichnological analysis of sea stars in the deep sea near the AT: behavioral insights from in situ observations (Miguez-Salas et al., 2024). we examined sea star traces from six deep-sea stations (deeper than 4500 m) near the AT (North Pacific). A total of six families were identified from still images. The majority of them were not observed producing any Lebensspuren or just pentameral impressions related to resting and feeding activities. Two members of the families Pterasteridae and Porcellanasteridae could be clearly characterized by a composite behavior resulting in contrasting Lebensspuren morphotypes.

Paleodictyon is one of the most iconic and widespread of trace fossils in the geological record. Within the study area, ***Paleodictyon* shows no apparent correlation with local environmental parameters. Finally, based on a worldwide morphological comparison, we conclude that the new *Paleodictyon* specimens represent distinct ichnospecies that are associated with the relatively eutrophic conditions in this region** documenting the importance of characterizing horizontal bioturbation for approaching global biogeochemical cycles and conservational strategies (Miguez Salas et al., 2024).

Their smaller size may reflect this more eutrophic setting in which sufficient food can be obtained from a smaller area in order to satisfy the energetic requirements of the tracemakers. If so, then *Paleodictyon* size may provide some assistance when interpreting paleoenvironmental conditions (Miguez-Salas, 2023).

Connectivity

Despite extreme depths and environmental gradients, connectivity across trench systems is high. Meiofauna such as kinorhynchs and nematodes occur on both sides of the AT, likely dispersing via currents like Aleutian upwellings (Sanchez et al.; Kwan et al., PROOCE). Although the AT and island chains act as partial barriers, species overlap between the Bering Sea and trench rims, and the wide distribution of molluscs, suggest limited restriction (Kamenev et al.; Sigwart et al., PROOCE).

Amphipod MOTUs link the AT to the KKT, Clarion–Clipperton Zone, and NW Pacific, with dispersal driven mainly by adult swimming as most amphipods and isopods lack planktonic larvae (Brix et al., 2021). Isopods show contrasting patterns: some taxa (Stenotanainae, haploniscids, Neotanaidae) range thousands of kilometers across basins, while others (macrostylids) are more restricted (Głuchowska & Błażewicz; Knauber et al.; Palacios-Theil et al., PROOCE). Even species like *Bathypsurus sonnei* demonstrate that barriers are not absolute (Brandt et al., 2025). Genetic data from Mesosignidae and *Eurycope* confirm low population differentiation across trenches (Kelch et al.; Ohta et al., PROOCE).

Overall, these findings highlight a complex connectivity network between the AT and KKT, but also between the Bering Sea and the North Pacific shaped by species mobility, geography, and oceanography.

References

- Bober J, Brandt A, Frutos I & Schwentner M, Diversity and distribution of Ischnomesidae (Crustacea: Isopoda: Asellota) along the Kuril-Kamchatka Trench – A genetic perspective, PROOCE 2019, <https://doi.org/10.1016/j.pocean.2019.102174>.
- Bonk F, Iwan F, Brandt A & Martínez Arbizu P, Meiofauna assemblages in and around the Aleutian Trench, with focus on Harpacticoida (Copepoda), PROOCE 2025, 103510, <https://doi.org/10.1016/j.pocean.2025.103510>.
- Brandt A, Di Franco D, Knauber H, Kaiser S & Kelch A, *Bathypsurus sonnei* sp. nov. – a new species of the rare deep-sea isopod genus (Crustacea, Isopoda, Asellota) from the Aleutian Trench, north-eastern Pacific with notes on the Bathypsurinae, Progress in Oceanography 2025, 234, <https://doi.org/10.1016/j.pocean.2025.103443>.

Brandt A, Jażdżewska AM, Kaiser S, Błażewicz M, Gerken S, Gluchowska K, Kelch A, Preikschart M, Knauber H, Kohlenbach K, Saeedi H, Helene S. Tandberg AHS & Di Franco D, Community composition and distribution of epi- and suprabenthic macrofauna in the bathyal, abyssal, and hadal zones of the northern North Pacific, *Progress in Oceanography* 2024, doi: <https://doi.org/10.1016/j.pocean.2024.103376>.

Brandt A, Chen C, Tandberg AHS, Miguez-Salas O & Sigwart JD, Complex sublinear burrows in the deep sea may be constructed by amphipods, *Ecology and Evolution* 2023, 13, e9867. <https://doi.org/10.1002/ece3.9867>.

Jakobsson M, Mohammad R, Karlsson M, Brandt A, Di Fraco D, et al., The International Bathymetric Chart of the Arctic Ocean Version 5.0., *Sci Data* 2024, 11, 1420, <https://doi.org/10.1038/s41597-024-04278-w>.

Knauber H, Schell T, Brandt A & Riehl T, Across trench and ridge: description of five new species of the *Haploniscus belyaevi* Birstein, 1963 species complex (Isopoda: Haploniscidae) from the Kuril-Kamchatka Trench region, *Arthropod Systematics and Phylogeny. Zoosyst. Evol.* 2025, 101 (2) 2025, 813–853, doi 10.3897/zse.101.137663.

Miguez Salas O, Rodríguez Tovar FJ, Ekdale AA, Kaiser S, Brandt A & Gooday AJ, Northernmost (Subarctic) and deepest record of *Paleodictyon*: paleoecological and biological implications, *Scientific Reports* 2023, Vol.: 13:7181, <https://doi.org/10.1038/s41598-023-34050-w>.

Miguez Salas O, Saeedi H, Brandt A & Riehl T, Seafloor bioturbation intensity on the deep-sea: more complex than organic matter”, *Limnology and Oceanography* 9999, 2024, 1–13, doi: 10.1002/lno.12632.

Mizuki Ohta, Kojima S, Kaiser S & Brandt A, A new Eurycope (Asellota: Munnopsidae) species from Japanese waters and the Bering Sea with intraspecific genetic divergence among local populations, *PROOCE* 2025.

Moreau C, Eichsteller A, Jossart Q, Saucède T, Courville E, O'Hara T, Martinez-Soares P, Brandt A, Mironov A & Dilman A, Deep-sea echinoderms (except holothurians) collected during the AleutBio expedition around the Bering Sea and the Aleutian Trench, *Progress in Oceanography* 2025, <https://doi.org/10.1016/j.pocean.2025.103530>.

Preikschart M, Di Franco D, Kelch A, Meißner K, Brandt A & Kaiser S, Abundance and composition of abyssal and hadal macroinbenthic assemblages in the eastern Aleutian Trench (NE Pacific) and adjoining Bering Sea, *Progress in Oceanography* 2025, 237, 103508, in press.

Scientific Output

List of Publications

Akdogan D, Brandt A & Kaiser S, A new species of *Austroniscus* Vanhöffen, 1914 (Isopoda, Asellota, Nannoniscidae Hansen, 1914) from abyssal depths of the Aleutian Trench, North-eastern Pacific with revelations on the genus and its global distribution, *Progress in Oceanography* (under review).

Bonk F, Iwan F, Brandt A & Martínez Arbizu P, Meiofauna assemblages in and around the Aleutian Trench, with focus on Harpacticoida (Copepoda), *Progress in Oceanography* 2025, 103510, <https://doi.org/10.1016/j.pocean.2025.103510>.

Bonk F, Iwan F, Khodami S, Brandt A & Martínez Arbizu P, Copepods Inside and Around a Trench: A Metabarcoding Survey of Meiofauna in the Aleutian Trench and Adjacent Regions, *Progress in Oceanography* (in press).

Brandt A, Jazdzewska AM, Kaiser S, Błażewicz M, Gerken S, Gluchowska K, Kelch A, Preikschart M, Knauber H, Kohlenbach K, Saeedi H, Helene S, Tandberg A & Di Franco D, Community composition and distribution of epi- and suprabenthic macrofauna in the bathyal, abyssal, and hadal zones of the northern North Pacific, *Progress in Oceanography* (2024),
doi: <https://doi.org/10.1016/j.pocean.2024.103376>.

Brandt A, Di Franco D, Knauber H, Kaiser S & Kelch A, *Bathyopsurus sonnei* sp. nov. – a new species of the rare deep-sea isopod genus (Crustacea, Isopoda, Asellota) from the Aleutian Trench, north-eastern Pacific with notes on the Bathyopsurinae, *Progress in Oceanography* 2025, 234,
<https://doi.org/10.1016/j.pocean.2025.103443>.

Di Franco D, Kaiser S, Kelch A, Preikschart M, Błażewicz M, Brenke N, Gerken S, Gluchowska K, Jeskulke K, Knauber H, Kohlenbach K, Tandberg AHS, Jazdzewska A & Brandt A, Ecological and spatial factors shaping abyssal and hadal peracarid crustacean communities in the eastern Aleutian Trench (NE Pacific), *Progress in Oceanography* (in press).

Jakobsson M, Mohammad R, Karlsson M, Brandt A, Di Franco D, et al., The International Bathymetric Chart of the Arctic Ocean Version 5.0. *Sci Data* 2024, 11, 1420. <https://doi.org/10.1038/s41597-024-04278-w>.

Knauber H, Brandt A & Riehl T, Traversing the North Pacific: Biogeography and connectivity patterns of deep-sea isopods across three trench systems, *Progress in Oceanography* 2025.

Kushida Y, Brandt A, Reimer J D, Kise H & Poliseño A, Taxonomic position of *Porcupinella profunda* with first record from the Aleutian Trench, *Progress in Oceanography* (under review).

Kwan YH, Trouche B, Wenzhöfer F, Middelboe M, Brandt A, Shimabukuro M, Derycke S, Glud RN & Zeppilli D, Trenches Apart, Yet Worm to Worm: Inter- and Intra-Trench Comparisons Reveal Divergent and Convergent Dynamics in Hadal Nematode Biodiversity *Progress in Oceanography* (under review).

Moreau C, Eichsteller A, Jossart Q, Saucède T, Courville E, O'Hara T, Martinez-Soares P, Brandt A, Mironov A & Dilman A, Deep-sea echinoderms (except holothurians) collected during the AleutBio expedition around the Bering Sea and the Aleutian Trench, *Progress in Oceanography* 2025, <https://doi.org/10.1016/j.pocean.2025.103530>.

Ohta M, Kojima S, Kaiser S & Brandt A, A new Eurycope (Asellota: Munnopsidae) species from Japanese waters and the Bering Sea with intraspecific genetic divergence among local populations, *Progress in Oceanography* (in press).

Praxedes RA, Du J, Brandt A, Karanovic I & Nunez Brandao S, Three new Trachyleberididae species (Crustacea, Ostracoda) species from the Aleutian Trench and Bering Sea, *Progress in Oceanography* (submitted).

Preikschat M, Di Franco D, Kelch A, Meißner K, Brandt A & Kaiser S, Abundance and composition of abyssal and hadal macroinbenthic assemblages in the eastern Aleutian Trench (NE Pacific) and adjoining Bering Sea, *Progress in Oceanography* (in press), 237 (2025) 103508, <https://doi.org/10.1016/j.pocean.2025.103508>.

Sanchez N, Bonk F & González-Casarrubios A, Kinorhyncha community in the Aleutian Trench (North Pacific Ocean) with the description of a new Cristaphyes species (Allomalorhagida, Pycnophyidae), *Progress in Oceanography* 2025.

Santín Muriel A, Theising F, Despujols D & Brandt A, A chance encounter: new *Spinularia* Gray, 1867 from abyssal depths of the Aleutian Trench (Beringmeer) leads to the proposal of new family, Spinulariidae fam nov, *Progress in Oceanography* 2025.

Sigwart JD, Schleuning M, Brandt A, Pfenninger M, Saeedi H, Borsch T, Häffner E, Lücking R, Güntsch A, Trischler H, Töpfer T & Wesche K, Collectomics Consortium, Collectomics – towards a new framework to integrate museum collections to

address global challenges, Natural History Collections and Museomics 2025, 2, 1–20, <https://doi.org/10.3897/nhcm.2.148855>.

Sindlev MB, Balmonte JP, Wenzhöfer F, Xiao W, Stief P, Oguri K, Tsuchiya M, Yokoyama Y, Canfield DE, Sanei H, Brandt A & Glud RN, The benthic environment of the Aleutian Trench region: Sediment provenance, organic carbon sources and deposition dynamics, Progress in Oceanography (submitted).

Theising FI, Hentschel U, Busch K, Brandt A, Carvalho F, Xavier JR & Santín A, Does an Arctic circumpolar distribution exist for deep-sea sponges? Unravelling the systematics of *Stylocordyla borealis* (Porifera: Demospongiae) through integrative taxonomy, Progress in Oceanography 2025.

List of conference presentations

2023 | **A new *Austroniscus* Vanhöffen, 1914 (Isopoda, Asellota, Nannoniscidae) species from the abyss of the Aleutian trench, NE Pacific.** GfBS, Frankfurt a. M., Germany

2023 | **Biodiversity of the North Pacific including new data from the abyss of the Aleutian trench, NE Pacific.** GfBS, Frankfurt a. M., Germany

2023 | **Diversity and distribution of Ischnomesidae (Crustacea: Isopoda) in the Beringmeer and along the Aleutian trench.** GfBS, Frankfurt a. M., Germany

2023 | **A new species of the isopod family Mesosignidae Schultz, 1969 (Crustacea, Malacostraca) from the Aleutian Trench, North Pacific.** GfBS, Frankfurt a. M., Germany

2023 | **Biodiversity of the North Pacific including new data from the abyss of the Aleutian trench, NE Pacific.** 6th World Conference on Marine Biodiversity, Penang, Malaysia

2023 | **In the trench and beyond: Meiofauna and Harpacticoida diversity within and around the Aleutian Trench.** 6th World Conference on Marine Biodiversity, Penang, Malaysia

2023 | **A Deep-sea isopod diversity patterns and connections from the Aleutian Trench.** 6th World Conference on Marine Biodiversity, Penang, Malaysia

2023 | **Abyssal-hadal connections: Delving deep into benthic isopod diversity of the northern Pacific Ocean.** A. International Crustacean Conference, Wellington, New Zealand

2024 | **Unveiling deep frontiers: initial insights into isopod diversity of the eastern Aleutian Trench (NE Pacific).** Crusttag, Rostock, Germany

2024 | **Biodiversity and biogeography of the abyssal and hadal Aleutian trench and adjacent N Pacific deep-sea regions.** Crusttag, Rostock, Germany

2024 | **Expeditions in stormy times – Deep-sea marine biological studies on biodiversity in the Aleutian Trench (AleutBio).** The Crustacean Society Summer meeting, Taipei, Taiwan

2024 | **On the move? Projecting distribution shifts of benthic shelf and deep-sea peracarid species in a changing North Pacific climate.** The Crustacean Society Summer meeting, Taipei, Taiwan

2024 | **The power of systematics in marine sciences.** Brandt, A. Gedenksymposium für den 40. Internationalen Preis für Biologie: “Phylogenie und Taxonomie (Die Welt der vielfältigen Organismen, einschließlich Pflanzen, Tiere, Pilze, Algen und Mikroben), Kyoto, Japan <https://www.kuba.co.jp/ipb2024/index.html>

2025 | **Deep-Sea Biodiversity in the Aleutian Trench (Aleutbio).** Brandt, A. 17 Deep-Sea Biology Symposium, Hong Kong

2025 | **Phylogeography and Systematics of the Mesosignidae Schultz, 1969: Survey of Isopod Diversity in North Pacific Trenches.** 17 Deep-Sea Biology Symposium, Hong Kong

2025 | **From barriers to biodiversity – phylogeographic patterns in deep-sea isopods in two major seas.** K17 Deep-Sea Biology Symposium, Hong Kong

2025 | **Building Alliances to Combat Marine Biodiversity Loss.** UNOC 3 (United Nations Ocean Conference), Nizza, France

2025 | **Robust species information for evidence-based decisions in marine conservation policy.** (side event auf Meteor): UNOC 3 (United Nations Ocean Conference), Nizza, France

2025 | **From isopods to deep-sea research – the power of systematics in marine sciences.** The Crustacean Society Summer Meeting, Paris, France

2025 | **A. Phylogeography and Systematics of the Mesosignidae Schultz, 1969: Survey of Isopod Diversity in North Pacific Trenches.** The Crustacean Society Summer Meeting, Paris, France

2025 | **Surprising Postmarsupial Developmental Strategies Described from the North Pacific of the Isopod Family Ischnomesidae Hansen, 1916.** Beyond the “norm”? The Crustacean Society Summer Meeting, Paris, France

Data

Continuous thermosalinograph oceanography (SMBs):
<https://doi.pangaea.de/10.1594/PANGAEA.965687>

Continuous optical chlorophyll-a and turbidity (SMBs):
<https://doi.pangaea.de/10.1594/PANGAEA.968755>

Multibeam bathymetry processed data:
<https://doi.pangaea.de/10.1594/PANGAEA.952448>

Multibeam bathymetry raw data:
<https://doi.pangaea.de/10.1594/PANGAEA.950196>

Sedimentology, mineralogy, and biogeochemistry:
<https://doi.pangaea.de/10.1594/PANGAEA.984610>

Biodiversity data:
<https://doi.org/10.15468/acfpyn> accessed via GBIF.org

Knauber H., Kohlenbach K., Yasuhara P., Lüter C., Werner R., Brandt A., Saeedi H. (2023a). Deep-sea benthic crustacean, polychaete, and sipunculid data from the Bering Sea. Deep-sea OBIS node. Sampling event dataset:
<https://doi.org/10.1016/j.seares.2022.102332>

Knauber, H., Kohlenbach, K., Brandt, A., & Saeedi, H. (2023b). Crustaceans of the Northwest Pacific Ocean: Species richness and distribution patterns. J. Sea Res. 191, 102332:
<https://doi.pangaea.de/10.1594/PANGAEA.954253>.

Brandt, Angelika (2023): Master tracks in different resolutions of SONNE cruise SO293, Dutch Harbour - Vancouver, 2022-07-22–2022-09-06 [dataset]. Senckenberg Research Institute and Natural History Museum, Frankfurt/M, PANGAEA:
<https://doi.org/10.1594/PANGAEA.954253>

Cruise Report

SO293: https://doi.org/10.48433/cr_so293

SO294

CLOCKS: Northern Cascadia extent of locked zone, prism deformation, slip-toe, and the edge of subduction & Cascadia CO₂: Seismic multi-parameter study at a possible site for CO₂ storage in basalt in the Cascadia Basin

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

M. Riedel, H. Kopp, D. Lange, M. Jegen, J. Bialas, M.S. Monfared, W. Schäfer, K. Reeck

Geological Survey of Canada – Pacific | Sidney, BC, Canada

K.L. Douglas, R.J. Enkin, M.M. Côté, A. Schaeffer, K. Wang, T. Sun

Japan Agency for Marine Earth Science and Technology | Yokohama, Japan

K. Obana, T. Takahashi

University of Tokyo | Tokyo, Japan

H. Shiobara

Kobe University | Kobe, Japan

H. Sugioka

Ocean Networks Canada | Victoria, BC, Canada

M. Scherwath

University of Alberta | Edmonton, AB, Canada

M.J. Unsworth

Institute of Ocean Sciences, Fisheries and Oceans Canada | Sidney, BC, Canada

C. Du Preez, H. Gartner, D. Labbé

CLOCKS

The SO294 – CLOCKS project involved a range of geophysical measurements and investigations off the west coast of Vancouver Island, British Columbia, Canada, to determine the nature and tectonic properties of the northern Cascadia subduction zone (Figure 1). The main focus is on the extent of the locked Juan de Fuca plate boundary, as this extent determines the magnitude of the next subduction earthquake. The maximum possible seaward limit of the rupture zone is the deformation front. Co-seismic displacement along the toe of the prism (“slip-to-toe”) as recently documented for the 2011 Tohoku-Oki earthquake (Kodaira et al., 2012) may also have occurred at Cascadia. The down-dip extent of seismogenic zones is often based on thermal models, using the 350°C isotherm as the deepest possible extent for rocks to accumulate seismic strain. As depicted in the conceptual model by Saffer and Tobin (2011), the locked zone may exhibit transition zones at the up- and down-dip limit depending on temperature, physical properties of the subducting sediments, or fluid-pressure along the fault zone. In order to determine the lower-bound of the locked zone, we combine measurements of the local seismicity with a set of ocean-bottom seismometers (OBS) deployed off Vancouver Island for the duration of ~10 months with magnetotelluric (MT) imaging of the sub-surface that reaches down to 30–40 km depth. For the first time, marine MT measurements were made in the northern Cascadia Subduction Zone and were combined with land-based observations made across Vancouver Island by the University of Alberta, considerably augmenting the legacy MT database acquired during the LITHOPROBE and EMSLAB projects (Kurtz et al., 1986, Wannamaker et al., 1989). The position of the subducting Juan de Fuca plate is clearly imaged in the new MT resistivity model. In addition, Vancouver Island is characterized as an area with high resistivity compared to the sedimentary accretionary wedge to the west that has a low resistivity. An area of low resistivity on the eastern margin of Vancouver Island can be associated with a fault zone. It forms the transition from the predominant igneous and metamorphic rocks of Vancouver Island to the Georgia Basin with the sedimentary rocks of the Nanaimo Group formation further to the east (Mustard, 1994). Incorporating the modeled temperature field of the Cascadia subduction zone allowed for porosity (i. e. fluid-content) to be derived along the MT-profile.

Imaging the region at the deformation front (DF) was accomplished using high-resolution multichannel seismic (MCS) and 3.5 kHz sub-bottom profiler (PARASOUND) data and multibeam mapping. The DF is compartmentalized into short segments, ~10 km in length, switching orientation and vergence of the underlying frontal thrust system. A prominent zone with a landward-verging main thrust is accompanied by a newly detected zone of proto-thrusts, reaching up to ~10 km to the west (seaward) of the DF. These proto-thrusts can accommodate some of the cumulative strain accumulation, possibly up to 20% based on

analyzing the velocity structure along legacy MCS data available in the region. North of this proto-thrust zone, a strike-slip fault was discovered by multibeam and PARASOUND imaging, extending from the DF through the accretionary prism. The strike-slip fault is rotated landwards by $\sim 35^\circ$ relative to the DF. This fault has a vertical seafloor offset of up to 20 m and may possibly accommodate some of the slip generated during a megathrust event. The fault is imaged in the new high-resolution MCS data as well as in legacy MCS data where it can be traced down to significant offsets in the top of crust.

The phenomena of low-frequency earthquakes or slow-slip at the shallow plate interface of subduction zones has been observed at locations such as the Izu-Bonin trench (Fukao et al., 2021). To investigate these types of slip phenomena at the plate boundary, an ocean bottom pressure gauge array was deployed during SO294 off Vancouver Island. Combined with coincident short-period OBS and a set of broad-band seismometers, a wide range of frequencies can be used to detect such slow earthquakes.

A second focus of SO294 is on the Explorer Plate and the Winona Basin, which is separated from the Juan de Fuca Plate by the Nootka Fault zone (Figure 1). Several geophysical measurements were used to investigate whether the Explorer Plate is subducted normally or is pushed under Vancouver Island by trans-pressure and whether there are subduction related earthquakes on the Explorer Plate that are decoupled from the Juan de Fuca Plate. A set of 11 OBS were deployed to determine the local seismicity, which was never done before across this region and known history earthquake locations were purely based on land-station recordings, thus limited to larger magnitudes and offset from true epicenter-locations due to a bias in the recording-azimuth. However, due to the significant delay in data availability due to military data screening after instrument recovery, results are pending. To date, a first AI-based analysis using PickBlue (Bornstein et al., 2024) of earthquake locations has been completed.

Two seismic refraction profiles with a total of 20 OBS locations were acquired to image the velocity structure of the Explorer plate subduction system. Top of crust was clearly imaged west of the deformation front in the coincident MCS data but the reflection is lost eastward. Mirror-imaging of the OBS data indicate a dipping crust east of the deformation front, too deep to be imaged with the MCS system used. The OBS data show continuous crustal first arrivals (P_g) and upper mantle phases (P_n) across both profiles. One land-station on Brooks-Peninsula, in line with the southern refraction profile, also recorded arrivals from the seismic data. It provides additional information on the position of the Explorer Plate within the region that we were unable to actively image due to regulatory restrictions.

Additional constraints on the depth of the oceanic crust can also be obtained from heat-flow data. Along the two seismic refraction lines, heat-flow was determined

at a total of 26 stations. Estimated heat-flow values decrease from west to east (150–70 mW/m²) indicating deepening of the oceanic crust and increasing sediment thickness. The gas hydrate related bottom-simulating reflector seen across the basin provides additional information to the heat-flow pattern. All information from the various observations will be combined into a new structural tectonic model of the Explorer Plate and Winona Basin system after completion of the OBS-based tomography and seismicity analyses. First analyses of the new multibeam, MCS, and heat-flow data already indicate that the Winona Basin east of the deformation front is under trans-pressure, as a set of en-echelon strike-slip faults was observed.

Possible earthquake recurrence rates were determined using turbidite events at local slope failure deposits at one ridge in the Winona Basin following previous approaches (Hamilton et al., 2015). Eight dated turbidites were correlated to contemporaneous deposits further south on the Juan de Fuca plate, but not all known turbidite events were also found in the deposits of the Winona Basin. Whether this is a sampling bias or whether earthquakes on the Explorer plate are decoupled from those on the Juan de Fuca plate cannot be determined with certainty at this stage. Additional samples from other slope failures are currently processed, which will refine the age model and interpretation.

Approximately 60 previously unknown cold seeps were discovered during SO294 using the multibeam echosounder systems, adding to the existing knowledge of gas venting along the Cascadia margin (Riedel et al., 2018). Some of the new gas venting sites showed gas flares rising for > 1000 m in the water column. Through collaboration with Fisheries and Ocean Canada, three of these new sites were visited with ROVs in subsequent cruises. Two sites investigated in water depths greater than 1500 m showed gas hydrate mounds at the seafloor. One location investigated on the Winona Ridge in water depths less than 650 m water was characterized by wide-spread carbonate platforms and was associated with a diverse habitat.

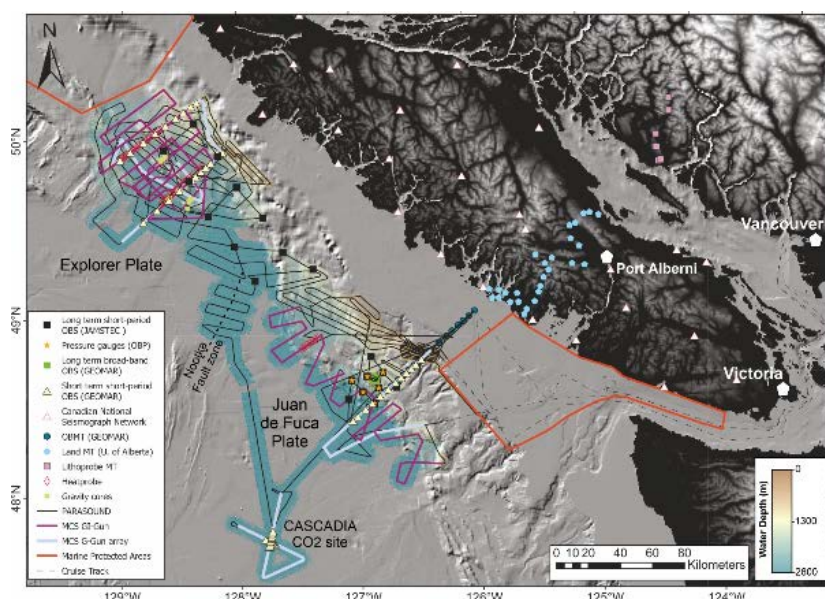


Figure 1: Cruise track of SO294 with data acquisition and instrumentation used. Background bathymetry shaded relief (Ryan et al., 2009) is overlain with data from SO294 shown in color.

Cascadia CO2

The second project completed during SO294 is a secondary-user project conducted in collaboration with Ocean Networks Canada (ONC). The CarbonSAFE Cascadia project lead by ONC investigates the potential of a site for CO₂ storage in the Cascadia Basin on the eastern flank of the Juan de Fuca Ridge (Figure 1). This initiative intends to conduct a test injection with supercritical CO₂. The available boreholes from IODP drilling expeditions 301 and 327 (Fisher et al. 2005; 2011) are aligned in a NNE direction along the strike of the ridge segments, but do not allow monitoring of the lateral extent of the injected gas plume. In order to avoid costly observation wells for an investigation of the physical parameters before and during the injection phase, geophysical remote sensing of subsurface parameters provide an adequate database for modeling and monitoring. The CASCADIA CO₂ project aims to investigate these possibilities. Along two perpendicular profiles, seismic refraction and reflection data were acquired. A total of 22 OBS were deployed. The OBS data yielded depth models of the subsurface structure and distribution of P- and converted S-wave velocities, as well as a model of the Vp/Vs ratio. The structures of the sediment cover to the reflection of the top of crust seen in the MCS data were modeled in the velocity profiles. Variations in the velocity-depth distribution indicate a slight structuring within the basement. Increased velocities below the seamounts Mama Bare and Baby Bare suggest that their roots extend to a depth of 3.5 km. The Moho is modeled at a depth of 10 km and shows a mostly layered stratification.

References

- Bornstein T, Lange D, Münchmeyer J, Woollam J, et al., PickBlue: Seismic phase picking for ocean bottom seismometers with deep learning, *Earth and Space Science* 2024, 11, e2023EA003332, doi:10.1029/2023EA003332.
- Fisher AT, Petronotis K, et al., Proceedings IODP 327, Tokyo (Integrated Ocean Drilling Program Management International, Inc.) 2011, doi:10.2204/iodp.proc.327.2011.
- Fisher AT, Urabe T, Klaus A, et al., Proceedings IODP 301, College Station TX (Integrated Ocean Drilling Program Management International, Inc.) 2005, doi:10.2204/iodp.proc.301.2005.
- Fukao Y, Kubota T, Sugioka H, Ito A, et al., Detection of “rapid” aseismic slip at the Izu-Bonin Trench, *Journal of Geophysical Research: Solid Earth* 2021, 126, e2021JB022132, doi:10.1029/2021JB022132.
- Hamilton TS, Enkin RJ, Riedel M, Rogers GC, et al., Slipstream: an early Holocene slump and turbidite record from the frontal ridge of the Cascadia accretionary wedge off western Canada and paleoseismic implications, *Canadian Journal of Earth Sciences* 2015, 52 (6), 405–430, doi:10.1139/cjes-2014-0131.
- Kurtz RD, DeLaurier JM & Gupta JC, A magnetotelluric sounding across Vancouver Island detects the subducting Juan de Fuca plate, *Nature* 1986, 321,596–599, doi: 10.1038/321596a0.
- Kodaira S, No T, Nakamura Y, Fujiwara T, et al., Coseismic fault rupture at the trench axis during the 2011 Tohoku-oki earthquake, *Nature Geoscience* 2012, 5, 646–650, doi:10.1038/NGEO1547.
- Mustard PS, The Upper Cretaceous Nanaimo Group, Georgia Basin, In Monger JWH (Eds.), *Geology and geological hazards of the Vancouver region, Southwestern British Columbia*, GSC Bulletin 1994, Vol. 481, 27–95. Geological Survey of Canada, https://publications.gc.ca/collections/collection_2024/rncan-nrcan/m42/M42-481-1994-eng.pdf.
- Riedel M, Scherwath M, Römer M, Veloso M, et al., Distributed natural gas venting offshore along the Cascadia margin, *Nature Communications* 2018, 9 (3264), doi:10.1038/s41467-018-05736-x.
- Ryan WBF, Carbotte SM, Coplan JO, O’Hara S, et al., Global Multi-Resolution Topography synthesis, *Geochem. Geophys. Geosyst.* 2009, 10, Q03014, doi: 10.1029/2008GC002332

Saffer DM & Tobin HJ, Hydrogeology and mechanics of subduction zone forearcs: fluid flow and pore pressure, *Annu. Rev. Earth Planet. Sci.* 2011, 39, 157–186, doi:10.1146/annurev-earth-040610-133408.

Wannamaker PE, Booker JR, Filloux JH, Jones AG, et al., Magnetotelluric observations across the Juan de Fuca Subduction System in the EMSLAB Project, *Journal of Geophysical Research* 1989, 94(B10), 14111–14125, doi:10.1029/JB094iB10p14111.

Scientific Output

List of Publications

Douglas K, Coté M, Riedel M, Podhorodeski A & Obana K, 2023003PGC cruise report: northern Cascadia Subduction Zone international research expedition, offshore British Columbia, Geological Survey of Canada, Open File, 90072. Natural Resources Canada, 2024, 124 pp., ISBN 978-0-660-69064-3, doi:10.4095/332361.

Kehew J, Douglas KL, Riedel M, Klauke I, et al., Swiftsure Bank water column survey SO294, offshore British Columbia, Geological Survey of Canada Open File 2023, 8943. 54 pp., doi:10.4095/331402.

Riedel M, Bialas J, Klein E, Papenberg C & Berndt J, Technical Report for Raw 2D MCS Reflection Data, R/V Sonne Cruise 294, Vancouver (Canada) – Port Hueneme (USA), 13/09/22–27/10/23, GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany, 37 pp., doi:10.3289/TR_2D-MCS_SO294.

List of conference presentations

2024 | Mapping Canada's West Coast Cold Seeps: new data for informed assessment International Symposium on Marine Geological and Biological Habitat Mapping (GeoHab '24), Arendal, Norway.

2024 | Ocean bottom seismograph and pressure gauge observations in northern Cascadia subduction zone Seismological Society of Japan Niigata, Japan.

2024 | Ocean bottom pressure gauge array observation for detecting slow earthquakes with a wide frequency range at Southwestern off the Vancouver Island American Geophysical Union Annual meeting, Washington, DC, USA.

2025 | **The role of proto-thrusts in strain accumulation along the segmented deformation front at the northern Cascadia subduction zone, Canada** German Geophysical Society, Bochum, Germany.

2025 | **Seismic activity off Vancouver Island in northern Cascadia subduction zone from seafloor observations** Seismological Society of Japan, Fukuoka, Japan.

Data

Master track cruise SO294:
<https://doi.org/10.1594/PANGAEA.958046>

2D multichannel seismic reflection data:
<https://doi.org/10.1594/PANGAEA.961490>

Water column data (EM 122):
<https://doi.org/10.1594/PANGAEA.965801>

Multibeam bathymetry data (EM122):
<https://doi.org/10.1594/PANGAEA.965800>

Water column data (EM710):
<https://doi.org/10.1594/PANGAEA.965790>

Multibeam bathymetry data (EM710):
<https://doi.org/10.1594/PANGAEA.965789>

Continuous optical chlorophyll-a and turbidity:
<https://doi.org/10.1594/PANGAEA.971781>

Continuous thermosalinograph oceanography:
<https://doi.org/10.1594/PANGAEA.960976>

Cruise Report

SO294: https://doi.org/10.48433/cr_so294

SO295

Nodule Monitoring 2 – Assessing the environmental impacts of polymetallic nodule mining

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany
M. Haeckel

Senckenberg am Meer | Wilhelmshaven, Germany
P. Martinez Arbizu

Max Planck Institute for Marine Microbiology | Bremen, Germany and Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany
F. Janssen

Federal Institute for Geosciences and Natural Resources (BGR) | Hannover, Germany
K. Schmidt

AND MiningImpact partners

Objectives

The research of the SO295 cruise was conducted in the context of the European collaborative project MiningImpact. In 2022 it investigated the environmental conditions and status of the polymetallic nodule associated ecosystem 1.5 years after the first industrial mining test executed by the Belgian company Global Sea Mineral Resources (GSR) in the Clarion-Clipperton Zone (CCZ) in the Northeast Equatorial Pacific. SO295 follows two previous cruises: In 2019 SO268 collected an extensive environmental baseline in the reference and trial sites, while in 2021 IP21 (BGR campaign MANGAN2021) monitored the Patania II nodule collection trials and performed a first impact assessment immediately after the tests. The project results are transferred into policy recommendations to inform e. g. the development of the Mining Code of the International Seabed Authority (ISA). The ISA was installed under the United Nations Convention on the Law of the Sea

(UNCLOS) to administer the exploration and exploitation of seabed mineral resources outside of the Exclusive Economic Zones (EEZs) of states and to protect the marine environment from harmful effects caused by those activities.

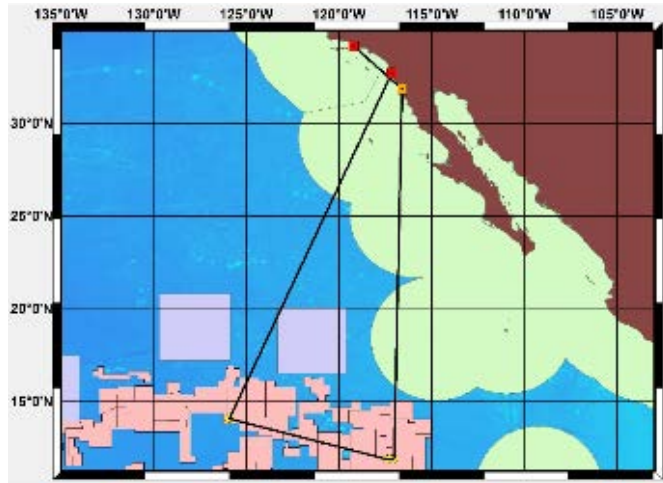


Figure 1: Bathymetric map of the eastern CCZ showing the cruise track and the working areas (yellow dots) in ISA license areas (red). Also shown are The Areas of Particular Environmental Interest (purple) and the EEZs of the USA, Mexico, and France (green).

Study Sites

The working areas of SO295 (Figure 1) are located in the “Prospective Area #1” of the contract area for polymetallic nodule exploration of the Federal Institute of Geosciences and Resources (BGR) and in the B4S03 area of the contract area of Global Sea Mineral Resources (GSR). In both working areas a trial site, consisting of a collector impact and a plume impact site, and a reference site were defined. While the GER trial and reference sites are located in water depths of 4060–4150 m exhibiting a smooth terrain with slopes of 0–3° and small nodules of typically less than 4 cm in size with an abundance of 20–26 kg/m² of wet weight (BGR, 2018), the BEL sites are located in water depths of 4410–4550 m exhibiting a rougher terrain with slopes of up to 3–7° and nodule sizes of more than 4 cm with an abundance of 20–24 kg/m² of wet weight (GSR, 2018). In the BGR area, Patania-II collected polymetallic nodules in an area of ~22,000 m², in the GSR area this area had a size of ~37,000 m². Since Patania-II did not have a riser pipe, the collected nodules were disposed as piles in the turns after each of the 50–60 m long mining lanes. Figure 2 shows the side-scan sonar images of the trial sites.

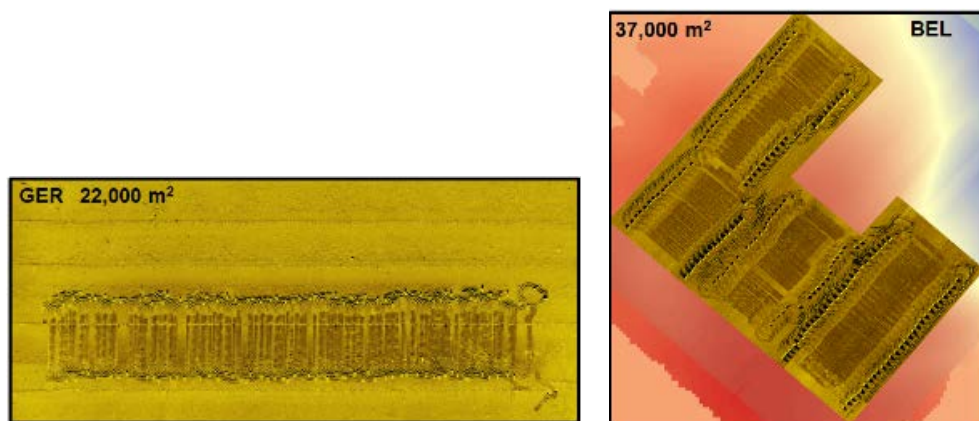


Figure 2: AUV-based side-scan sonar images of the collector trial sites in the BGR (top) and GSR (right) working area. Darker color indicates lower acoustic backscatter, i. e. where nodules and surface sediment have been removed. Black dots depict deposited nodule piles at the end of the mining lanes.

A comprehensive set of oceanographic, biological, microbiological, biogeochemical, and geological investigations was carried out. Bottom water samples were collected with a CTD rosette and a Bottom Water Sampler (BWS) while sediments were sampled with a box corer and a TV-guided multiple corer. ROV Kiel 6000 was deployed extensively for sampling of push core sediments, nodules, and benthic megafauna as well as for conducting in situ oxygen measurements, trace metal sampling, and benthic food web and novel restoration experiments. AUV Abyss was used for side-scan sonar imaging and photographic mapping of the seafloor, and the OFOS system for habitat surveying.

Results

Research in the Clarion-Clipperton Zone and other nodule areas of the Pacific Ocean has documented unique faunal assemblages associated with the polymetallic nodule hard substrate as well as many rare species (Vanreusel et al., 2016; Christodoulou et al., 2020; Brix et al., 2020; Rabone et al., 2023). Taxonomic analyses indicate higher epifauna abundances and a different community composition in nodule areas compared to areas without nodules: while soft corals, sponges, and ophiuroids dominate communities in nodule habitats, sea anemones and holothurians are more dominant in soft sediments. This appears to be a direct consequence of nodule surfaces being inhabited by sessile organisms, thereby forming a specific habitat for certain fauna (Kuhn et al., 2020). In addition, smaller infauna organisms, such as nematodes, copepods, and polychaetes that live in the sediments are more abundant in areas with low nodule density (Uhlenkott et al., 2020). Overall, nodule abundance appears to be of second-order importance for faunal densities after food supply. This is evident in a west-to-east and

south-to-north decreasing surface ocean productivity gradient, which determines the organic matter flux to the seafloor in the Clarion-Clipperton Zone. In return, benthic oxygen consumption as most important measure for microbial organic matter remineralization shows the same trend (Volz et al., 2020). Biodiversity is high for all size classes with more than 90% of sampled metazoan species and several higher taxa being undescribed (Rabone et al., 2023; Christodoulou et al., 2019). DNA analysis has shown that many species are found across the CCZ, however, assessing population and ecological connectivity remains limited by the high habitat variability, a patchy sampling scheme, and the high proportion of undescribed species (Gollner et al., 2017). Overall, environmental variability is high on local to regional scale in the CCZ (Uhlenkott et al., 2021).

Impacted sites of the Patania II trials were categorized qualitatively into “collector impact” (the mining area where the collector removed nodules and surface sediment with fauna) and “plume impact” (the area outside the mined area, where a thick sediment cover was deposited on top of the pristine seafloor). Substantial sediment deposition was observed within the first 500 m, fading out with increasing distance, but visually still identifiable on AUV photos up to distances of 2–3 km (Gazis et al., 2025).

The abundance of meio-, macro, and megafauna is strongly reduced in the collector impact site compared to pre-impact data of the trial sites and reference sites, while slightly increased meiofaunal abundances were found in the thick plume impact sites (Lefaible et al., 2024) that persisted also 1.5 years later. The reason for this observation is not clear at the moment. Possible explanations are that the small fauna fraction suspended with the sediment was preferentially deposited in the close vicinity of the mined area, i. e. behaving as rapidly sinking large particles, or that the fauna in the buried surface sediments is migrating upwards into the deposited sediment layer towards the new sediment surface to avoid suffocation. From our data it is currently also not clear, if the fauna (or parts of it) has survived the nodule collection and sediment suspension process.

Dissolved oxygen concentrations measured immediately and 1.5 years after the trials indicate diffusion of oxygen into the deeper sediment layers in the collector impact sites, thus indicating strongly reduced microbial remineralization of organic carbon in the mining area. This is corroborated by a reduced peak of nitrite concentrations in the porewater as well as lower labile organic matter content (i. e. lower food quality) than in the pre-impact situation. This provides, for the first time, data supporting our previous model predictions suggesting that recovery of the biogeochemical processes and fluxes takes several thousand years and is essentially controlled by the re-establishment of the reactive (bioturbated) surface layer through sedimentation (<0.5 cm/kyr) of labile organic matter (König et al., 2001; Haffert et al., 2020; Volz et al., 2020). In contrast, dissolved oxygen consumption is elevated in the thick plume impact sites. Unfortunately, this does

not yet shed light on the question, if the fauna has survived the nodule collection and sediment suspension process or not. Overall, the caterpillar track imprints of Patania-II added significant small-scale spatial variability to all benthic data, thereby complicating the interpretation.

Dissolved trace metal concentrations in sediment porewater showed a significant decrease in the collector impact area immediately after the impact related to the removal of the reactive surface sediment. The trace metal distribution in these settings 1.5 years after the trials indicates a re-establishment of the characteristic natural surface sediment enrichment (Paul et al., 2024), although at different rates for different elements related to the specific biogeochemical processes controlling porewater trace metal concentrations. In the plume impact sites, the concentrations of elements directly controlled by organic matter remineralization (e. g., Cu, V) decreased 1.5 years after the impact, whereas Mn and associated metals, such as Co, increased. In addition to the described impact assessments, more baseline data was obtained substantially adding to our understanding of the natural temporal and spatial variability in the two contract areas.

A thorough integration and interpretation of the data from the upcoming 5-yr post-impact cruise (SO322) with those from SO268, IP21 and SO295 will help to further constrain and quantify the effects of deep-sea mining on biogeochemical functions, faunal diversity and ecosystem functioning in a holistic way and how they will evolve over time.

Policy Work

The scientific results have been presented regularly at Annual Meetings or Workshops of the ISA and have been discussed with the different stakeholder groups (authorities, industry, NGOs) – for examples, please see presentation list below. Recommendations for the ISA Mining Code have been presented also as reports (e. g., Schmidt et al., 2025) or flyers and posters. MiningImpact scientists have also been selected by the ISA to directly contribute to first drafts of Standards and Guidelines of the Mining Code.

References

Brix S, Osborn KJ, Kaiser S, Truskey SB, et al., Adult life strategy affects distribution patterns in abyssal isopods – implications for conservation in Pacific nodule areas, *Biogeosciences* 2020, 17, doi:10.5194/bg-17-6163-2020.

Bundesamt für Geowissenschaften und Rohstoffe (BGR) Environmental Impact Assessment for the Testing of a Pre-prototype Manganese Nodule Collector Vehicle

in the Eastern German License Area (Clarion-Clipperton Zone) in the Framework of the European JPI-O MiningImpact 2 Research Project, 2018, Hannover, Germany, 209p.

Christodoulou M, O' Hara TD, Hugall AF & Martinez Arbizu P, Dark biodiversity in an abyssal mine field, *Current Biology* 2019, 29, doi:10.1016/j.cub.2019.09.012.

Christodoulou M, O' Hara T, Khodami S, Rodrigues CF, et al., Unexpected high abyssal ophiuroid diversity in polymetallic nodule fields of the Northeast Pacific Ocean, and implications for conservation, *Biogeosciences* 2020, 17, doi: 10.5194/bg-17-1845-2020.

Gazis I-Z, de Stigter H, Mohrmann J, Heger K, et al., Monitoring benthic plumes, sediment redeposition and seafloor imprints caused by deep-sea polymetallic nodule mining, *Nature Communications* 2025, 16, doi:10.1038/s41467-025-56311-0.

Global Sea Mineral Resources (GSR), Environmental Impact Statement: Small-scale Testing of Nodule Collector Components on the Seafloor of the Clarion-Clipperton Fracture Zone and its Environmental Impact, 2018, ISA_EIA_2018_GSRNOD2019, Zwijndrecht, Belgium, 337p.

Gollner S, Kaiser S, Menzel L, Jones DOB, et al., Resilience of benthic deep-sea fauna to mining activities, *Marine Environmental Research* 2017, 129, doi: 10.1016/j.marenvres.2017.04.010.

Haffert L, Haeckel M, de Stigter H & Janßen F, Assessing the temporal scale of deep-sea mining impacts on sediment biogeochemistry, *Biogeosciences* 2020, 17, doi:10.5194/bg-17-2767-2020.

König I, Haeckel M, Lougear A, Suess E, et al., A geochemical model of the Peru Basin deep-sea floor - and the response of the system to technical impacts, *Deep Sea Research Part II: Topical Studies in Oceanography* 2001, 48, doi:10.1016/S0967-0645(01)00065-0.

Kuhn T, Uhlenkott K, Vink A, Rühlemann C, et al., Chapter 58: Manganese nodule fields from the Northeast Pacific as benthic habitats, In: *Seafloor Geomorphology as Benthic Habitat*, 2020, Elsevier, 933-947, doi:10.1016/B978-0-12-814960-7.00058-0.

Lefaible N, Macheriotou L, Pape E, Molari M, et al., Industrial mining trial for polymetallic nodules in the Clarion-Clipperton Zone indicates complex and variable disturbances of meiofaunal communities, *Frontiers In Marine Science* 2024, 11, doi: 10.3389/fmars.2024.1380530.

Paul SA, Schmidt K, Achterberg EP & Koschinsky A, The importance of the soluble and colloidal pools for trace metal cycling in deep-sea pore waters, *Frontiers Marine Science* 2024, 11, doi:10.3389/fmars.2024.1339772.

Rabone M, Wiethase JH, Simon-Lledo E, Emery AM, et al., How many metazoan species live in the world's largest mineral exploration region?, *Current Biology* 2023, 33, doi:10.1016/j.cub.2023.04.052.

Schmidt K, Hauton C, Mestre N, Raimundo J, Paul S, Clark M, Laugesen J, Gaetano P, Egger L & Haeckel M, Ecotoxicological impacts of deep-sea mining: current scientific knowledge and necessary steps towards the definition of regulatory thresholds, 2025, 327 p, doi:10.5281/zenodo.15871149.

Uhlenkott K, Vink A, Kuhn T, Martínez Arbizu P, et al., Predicting meiofauna abundance to define preservation and impact zones in a deep-sea mining context using random forest modelling, *Journal of Applied Ecology*, 2020, 57, doi:10.1111/1365-2664.13621.

Uhlenkott K, Vink A, Kuhn T, Gillard B, et al., Meiofauna in a potential deep-sea mining area - influence of temporal and spatial variability on small-scale abundance models, *Diversity* 2021, 13, doi:10.3390/d13010003.

Vanreusel A, Hilario A, Ribeiro PA, Menot L, et al., Threatened by mining - polymetallic nodules are required to preserve abyssal epifauna, *Scientific Reports* 2016, 6, doi:10.1038/srep26808.

Volz JB, Haffert L, Haeckel M, Koschinsky A, et al., Impact of small-scale disturbances on geochemical conditions, biogeochemical processes and element fluxes in surface sediments of the eastern Clarion-Clipperton Zone, Pacific Ocean, *Biogeosciences* 2020, 17, doi:10.5194/bg-17-1113-2020.

Scientific Output

List of Publications

Chen Z, Baeza JA, Chen C, Gonzalez MT, et al., A genome-based phylogeny for Mollusca is concordant with fossils and morphology, *Science* 2025, 387, doi:10.1126/science.ads0215.

Christodoulou M, Mah C & Martinez Arbizu P, Two new *Caymanostella* species discovered at deep-sea wood falls in the Clarion Clipperton Fracture Zone, *Scientific Reports* 2025, 15, doi:10.1038/s41598-025-00753-5.

Cuvelier D, Zurowietz M & Nattkemper TW, Deep learning-assisted biodiversity assessment in deep-sea benthic megafauna communities: a case study in the context of polymetallic nodule mining, *Frontiers in Marine Science* 2024, 11, doi:10.3389/fmars.2024.1366078.

Gazis I-Z, de Stigter H, Mohrmann J, Heger K, et al., Monitoring benthic plumes, sediment redeposition and seafloor imprints caused by deep-sea polymetallic nodule mining, *Nature Communications* 2025, 16, doi:10.1038/s41467-025-56311-0.

González-Casarrubios, A, Martinez Arbizu P & Sánchez N, *Mixtophyes toothlessi* sp. n., a new Kinorhyncha species (Anomoirhaga: Neocentrophyidae) from the Clarion-Clipperton Zone, with a revision of terminology and taxonomic features of the family, *Zootaxa* 2023, 5285 (1), 149–160, <https://doi.org/10.11646/zootaxa.5285.1.6>.

Lefaible N, Macheriotou L, Pape E, Molari M, et al., Industrial mining trial for polymetallic nodules in the Clarion-Clipperton Zone indicates complex and variable disturbances of meiofaunal communities, *Frontiers in Marine Science* 2024, 11, doi: 10.3389/fmars.2024.1380530.

Metaxas A, Anglin CD, Cross A, Drazen J, et al., Comparing environmental impacts of deep-seabed and land-based mining: A defensible framework, *Global Change Biology* 2024, 30, doi:10.1111/gcb.17334.

O'Hara TD, Hugall AF, Haines ML, et al., Spatiotemporal faunal connectivity across global sea floors, *Nature* 2025, 645, 423–428, <https://doi.org/10.1038/s41586-025-09307-1>.

Paul SA, Schmidt K, Achterberg EP & Koschinsky A, The importance of the soluble and colloidal pools for trace metal cycling in deep-sea pore waters, *Frontiers in Marine Science* 2024, 11, doi:10.3389/fmars.2024.1339772.

Schmidt K, Hauton C, Mestre N, Raimundo J, Paul S, Clark M, Laugesen J, Gaetano P, Egger L & Haeckel M, Ecotoxicological impacts of deep-sea mining: current scientific knowledge and necessary steps towards the definition of regulatory thresholds, 2025, 327 p, doi:10.5281/zenodo.15871149.

Uhlenkott K, Simon-Lledó E, Vink A, et al., Habitat heterogeneity enhances megafaunal biodiversity at bathymetric elevations in the Clarion Clipperton Fracture Zone, *Mar. Biodivers.* 2023, 53, 55. <https://doi.org/10.1007/s12526-023-01346-z>.

Uhlenkott K, Meyn K, Vink A, et al., A review of megafauna diversity and abundance in an exploration area for polymetallic nodules in the eastern part of the Clarion Clipperton Fracture Zone (North East Pacific), and implications for potential future deep-sea mining in this area, *Mar. Biodivers.* 2023, 53, 22, <https://doi.org/10.1007/s12526-022-01326-9>.

List of conference presentations

2025 | **Environmental impacts of deep-sea mining** 30th Annual Meeting of the International Seabed Authority, Kingston, Jamaica.

2025 | **Environmental impacts of deep-sea mining: from scientific research to policy recommendations** One Ocean Science Congress, Nice, France.

2025 | **Short-term impacts of polymetallic nodule mining on sediment remineralization activity: in situ observations of benthic oxygen fluxes after a nodule collector prototype trial in the Clarion-Clipperton Fracture Zone** One Ocean Science Congress, Nice, France.

2025 | **Environmental monitoring of DSM operations: experiences from nodule collector tests and the ongoing discussion on thresholds** ISA Expert Workshop on Monitoring Technologies, Kobe, Japan.

2025 | **Impacts on the benthic ecosystem: scales, indicators, threshold values, and gaps** The Prospectors & Developers Association Canada Conference (PDAC 2025), Toronto, Canada.

2024 | **Short-term impacts of deep-sea mining on sediment remineralization activity: in situ observations of benthic oxygen uptake after a nodule collector prototype test in the Clarion-Clipperton Fracture Zone** Ocean Sciences Meeting, New Orleans, USA.

2023 | **Impacts on the benthic ecosystem: scales, indicators, threshold values, and gaps** 28th Annual Meeting of the International Seabed Authority, Kingston, Jamaica.

Data

SO295 track:

<https://doi.pangaea.de/10.1594/PANGAEA.961800>

<https://doi.pangaea.de/10.1594/PANGAEA.961801>

Ship multibeam echosounder data:

<https://doi.pangaea.de/10.1594/PANGAEA.965805>

Ship ADCP data:

<https://doi.pangaea.de/10.1594/PANGAEA.962919>

<https://doi.pangaea.de/10.1594/PANGAEA.962920>

Ship underway data:

<https://doi.pangaea.de/10.1594/PANGAEA.972092>

<https://doi.pangaea.de/10.1594/PANGAEA.965688>

Sediment pigments:

<https://doi.pangaea.de/10.1594/PANGAEA.982348>

Sediment grain size:

<https://doi.pangaea.de/10.1594/PANGAEA.982349>

Sediment CN element content:

<https://doi.pangaea.de/10.1594/PANGAEA.982347>

Seawater REY concentrations:

<https://doi.pangaea.de/10.1594/PANGAEA.982623>

Seawater Nd isotope signature:

<https://doi.pangaea.de/10.1594/PANGAEA.981265>

Sediment organic compound chemistry:

<https://doi.pangaea.de/10.1594/PANGAEA.983938>

AUV CTD sensors:

<https://doi.pangaea.de/10.1594/PANGAEA.971853>

<https://doi.pangaea.de/10.1594/PANGAEA.971867>

<https://doi.pangaea.de/10.1594/PANGAEA.971861>

<https://doi.pangaea.de/10.1594/PANGAEA.971859>

<https://doi.pangaea.de/10.1594/PANGAEA.971865>

<https://doi.pangaea.de/10.1594/PANGAEA.971868>

<https://doi.pangaea.de/10.1594/PANGAEA.971870>

<https://doi.pangaea.de/10.1594/PANGAEA.971856>

<https://doi.pangaea.de/10.1594/PANGAEA.971857>

<https://doi.pangaea.de/10.1594/PANGAEA.971864>

<https://doi.pangaea.de/10.1594/PANGAEA.971871>

<https://doi.pangaea.de/10.1594/PANGAEA.971869>

<https://doi.pangaea.de/10.1594/PANGAEA.971860>

<https://doi.pangaea.de/10.1594/PANGAEA.971855>

<https://doi.pangaea.de/10.1594/PANGAEA.971866>

<https://doi.pangaea.de/10.1594/PANGAEA.971863>

Cruise Report

SO295: https://doi.org/10.48433/cr_so295

SO296

Impact of pelagic Anoxia in the Upwelling Area off Concepción and in a pristine anoxic Fjord, and the postglacial Development of the Patagonian Fjord Region of Chile (MAPUCHE)

Authors

Leibniz Institute for Baltic Sea Research Warnemünde | Rostock, Germany

H. N. Schulz-Vogt, H. W. Arz

Universidad de Concepción | Concepción, Chile

S. Pantoja, C. B. Lange

Goals of the cruise

The SO296 expedition pursued two main scientific objectives across three contrasting marine environments along the Chilean coast. The first objective, addressed in Working Areas 1 and 2 (Figure 1), was to determine how oxygen-depleted to anoxic conditions shape biogeochemical cycles in the water column. This included studying the transformation and degradation of organic matter, the functioning of microbial communities, and the consequences for food webs and biodiversity. In both areas, the team conducted high-resolution chemical profiling, including nutrient and oxygen measurements, and performed microstructure-based turbulence measurements to understand mixing processes that regulate biogeochemical transformations. In the seasonal upwelling system off Concepción (Area 1), these approaches were applied to a well-defined oxygen minimum zone. In the stratified Golfo Almirante Montt (Area 2), they were used to capture how physical stratification, freshwater inputs, and limited deep-water ventilation influence microbial activity, methane dynamics, and elemental cycling.

The second objective, addressed in Working Areas 2 and 3, focused on reconstructing the postglacial development of the Patagonian fjord region. This work examined how changing atmospheric and oceanic circulation patterns, glacier dynamics, sea-level rise, and regional isostatic uplift shaped fjord morphology and sedimentary environments since the last ice age. Extensive geophysical surveys – multibeam mapping, sediment acoustics – and sediment coring in Golfo Almirante Montt and the Canal Concepción/Canal Wide/Seno Eyre (CWE) system enabled the reconstruction of long-term sedimentation histories and the identification of tectonic and glacial controls on basin evolution.

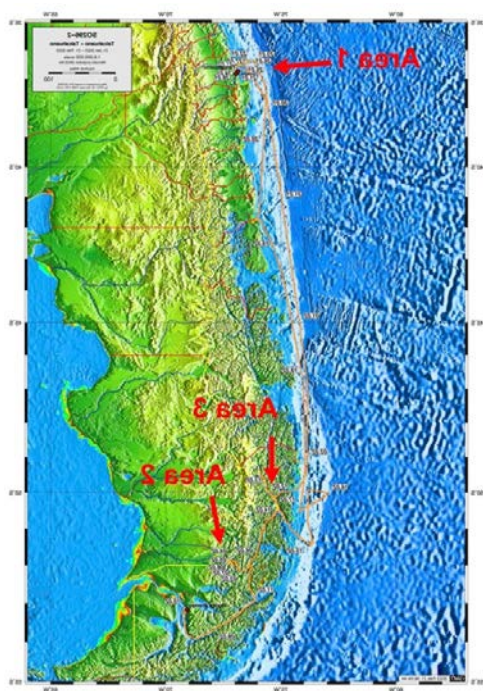


Figure 1: Map showing the location of the three working areas.

Results from Working Area 1

Bottom waters were strongly oxygen-depleted but remained free of measurable hydrogen sulfide, indicating a sulfide-poor OMZ environment at the time of sampling.

Macrozoobenthic communities showed distinct patterns across the OMZ gradient, with polychaetes dominating the core OMZ and higher species richness at stations where oxygen levels increased. These patterns reflect how low oxygen constrains benthic assemblages and community structure along the continental

margin off 36°S (Krug & Zettler 2025). Sediment samples yielded notable bivalve records, including the re-establishment of the endemic *Malletia sorrow* and the first Chilean record of the cuspidariid genus *Cardiomya*, the latter described as a new species from material collected in this working area (Zettler 2024; Zettler 2025). Biogeochemical profiles showed sharp vertical gradients in oxygen and nutrient concentrations, and microstructure turbulence measurements indicated that small-scale mixing influences the supply of electron acceptors and organic matter to the seafloor, shaping benthic processes. Pelagic net sampling revealed vertical structuring of zooplankton and micronekton, with several taxa concentrated near the upper OMZ boundary, suggesting behavioral or physiological responses to low oxygen. These patterns underscore the strong coupling between oxygen conditions and both benthic and pelagic components of the ecosystem in this eastern boundary upwelling system.

Results from Working Area 2

High-resolution CTD and pump-CTD profiles showed a strongly stratified fjord with fully oxic waters but distinct oxygen minima (ca 50 $\mu\text{mol L}^{-1}$) between 80–180 m in the northwestern basin, where exchange with the open ocean is most limited. Just below the photic zone, elevated nitrite and ammonium peaks indicated zones of intense heterotrophic remineralization and nitrification, driven by sinking particle fluxes and associated microbial activity.

Methane mapping revealed a clear CH_4 -enrichment layer (20–80 m) with maxima up to 21 nM at station GAM-21, likely linked to seepage structures identified at basin edges. CH_4 oxidation rate measurements showed highest microbial turnover within this enrichment layer, while deep-water rates were near detection limits. High-resolution sampling allowed the identification of narrow vertical zones where microbial methane oxidation forms an effective pelagic filter. Physical mixing, basin morphology, and microbial community structure jointly regulate methane transport and oxidation, confirming that fjord stratification and episodic intrusions critically shape biogeochemical processes in this oxygen-poor system (Schmale et al., 2025).

The depositional conditions in the western basin of the GAM show largely undisturbed sedimentation, except for the marginal areas. All four gravity cores reveal a largely undisturbed, radiocarbon-dated Late Glacial to Holocene sequence of predominantly terrigenous sediment, documenting the glacier retreat in the western sector of the South Patagonian Ice Sheet and the establishment of marine, partially hypoxic depositional conditions. The postglacial development of the GAM can be exemplarily shown with sediment core SO296-2/57-6 (Figure 2; deepest point of the GAM; Kaiser et al., submitted). Compositional changes reflect distinct phases of postglacial fjord evolution. In the lowermost sections, an increase in

terrigenous input likely related to glacier advances at the onset of the Antarctic Cold Reversal (ACR) (e. g., Pedro et al., 2015; Moreno et al., 2009). A marked decline in terrigenous input indicates the somewhat delayed end of the ACR phase. A final transition from glacio-lacustrine to fjord-marine sedimentation in this region occurs around 10 ka BP. Applying a proxy based on soil bacterial lipids on the core, Mean Air Temperatures (MAT) warmed by ca. 5°C during this interval and reached maximum values around $12\pm1^\circ\text{C}$ during the early Holocene (11–8 kyr) and around $10\pm1^\circ\text{C}$ during the mid- to late Holocene (Figure 2c). Combined with the K/Ti proxy for terrigenous input (Figure 2d) as well as two proxies for vegetation cover based on n-alkane lipids derived from higher plant leaf waxes (Figure 2ef) an increased humidity between 14.5–11 kyr and drier conditions during the early Holocene are indicated, in contradiction with generally wetter conditions in south-western, coastal Patagonia at this time (e. g., Lamy et al., 2010; Perren et al., 2025). Drier/wetter conditions in the lee/wind side of the austral Andes may result from a strengthening of foehn winds during the early Holocene in relation to a positive Southern Annular Mode and the resulting poleward shift, contraction and strengthening of the Southern Hemisphere Westerly Winds.

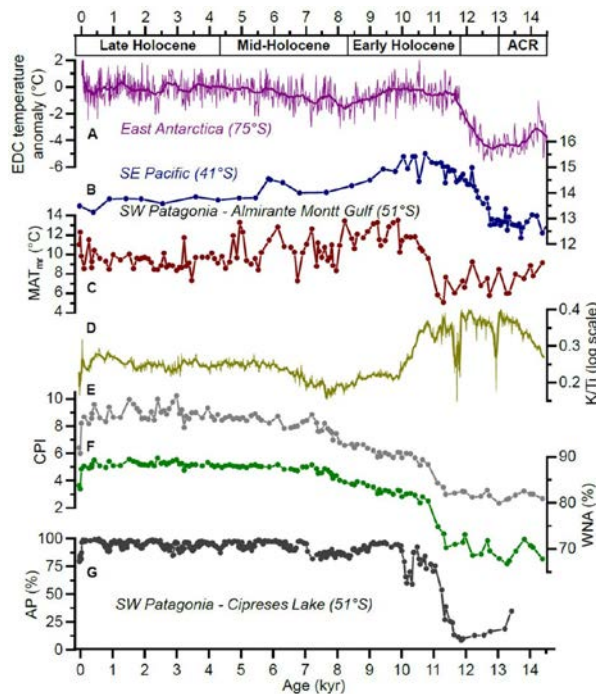


Figure 2: Almirante Montt Gulf and other key proxy records from south-western Patagonia and Antarctica. (A) Antarctic air temperature (EPICA Dome C; Jouzel et al., 2007), (B) Southeast Pacific sea surface temperature (SST) (41°S off southern Chile; Kaiser et al., 2005), (C) mean air temperature (MATmr) estimation based on soil-derived brGDGTs (this study), (D) K/Ti (this study), (E) carbon preference index (CPI; this study), (F) percentage of leaf wax n-alkanes (WNA; this study), (G) percentage of arboreal pollen (AP) – Lake Cipreses (Moreno et al., 2018).

Three short cores from the western part of the GAM were analysed for sub-recent sedimentation processes. The stratigraphic correlation of these short cores is based on gamma-spectrometric measurements of the radioisotopes ^{210}Pb , ^{137}Cs , and ^{241}Am . TOC and Hg show a marked increase in all three cores during the past ~70 years. On average, sedimentation rates amount to ~3 mm/a. Major and trace element analyses (SO296-2/57-1MUC-3 and Frahm core 57-4FL) indicate the formation of various authigenic minerals, particularly in the upper ~15 cm, which are rich in organic matter. In the upper 3 cm, Mn oxides are enriched, while in deeper sections parallel enrichments of Mn, Ca, and inorganic total carbon indicate layers containing Mn carbonate. These Mn-Ca-carbonate layers likely formed through bacterially mediated reduction of Mn oxide under slight H_2S presence in the underlying sediments (Henkel et al., 2019). The variability of the observed diagenetically formed mineral phases indicates pronounced redox fluctuations over the past decades, which have also strongly influenced the signatures of redox-sensitive trace metals (Dellwig et al., 2021). In the Late Holocene section, distinct Mn enrichments point to episodic formation of manganese carbonates under intermittently hypoxic conditions (Figure 3; Stöcker, 2025). Such Mn carbonates are also described from the modern and mid-to late Holocene central Baltic Sea sediments (e. g., Häusler et al., 2018), where they form through interactions between oxygen-rich saline and brackish-anoxic bottom waters.

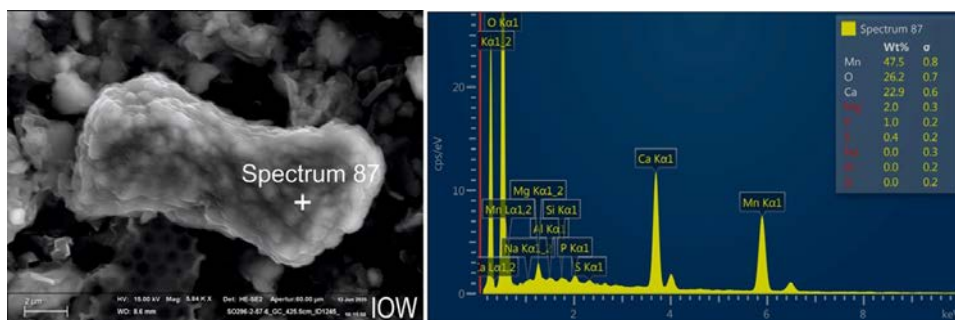


Figure 3: Example of an Mn-Ca-carbonate particle identified by SEM-imaging and EDX elemental composition in sample SO296-2_57-6_GC_425.5-cm_ID1245; scale bar is 2 μm .

Results from Working Area 3

CWE is characterized by a rugged morphology in which steep ridges of crystalline basement transition into smooth, elongated, sediment-filled basins. The shallowest areas are located in the north, near the glacier front of the Pío XI Glacier (approximately 300 m depth). Initial results are available from this part of the CWE system. The Pío XI Glacier (49°S) is the largest and one of the few advancing glaciers in Patagonia. Satellite data suggest that around the year 2010, the terminus of the main glacier transitioned from directly calving into the fjord to a land-based

terminus, leading to the formation of an ice-contact delta at the head of the Eyre Fjord. A comparison of earlier sub-bottom acoustic data and sediment cores with the data and samples obtained during cruise SO296-2 reveals a relatively abrupt increase in the number and magnitude of turbidity currents, coinciding with the formation of the ice-contact delta (Piret et al., 2024).

References

Dellwig O, Wegwerth A & Arz HW, Anatomy of the Major Baltic Inflow in 2014: Impact of manganese and iron shuttling on phosphorus and trace metals in the Gotland Basin, Baltic Sea, *Continental Shelf Research* 2021, 223, 104449.
Doi:10.1016/j.csr.2021.104449.

Häusler K, Dellwig O, Schnetger B, Feldens P, Leipe T, Moros M, Pollehne F, Schöнке M, Wegwerth A & Arz HW, Massive Mn carbonate formation in the Landsort Deep (Baltic Sea): Hydrographic conditions, temporal succession, and Mn budget calculations, *Mar. Geol.* 2018B, 395, 260-270, doi: 10.1016/j.margeo.2017.10.010.

Henkel JV, Dellwig O, Pollehne F, Herlemann DPR, Leipe T & Schulz-Vogt HN, A bacterial isolate from the Black Sea oxidizes sulfide with manganese(IV) oxide, *PNAS* 2019, DOI: 10.1073/pnas.1906000116.

Jouzel J, Masson-Delmotte V, Cattani O, Dreyfus G, Falourd S, Hoffmann G, Minster B, Nouet J, Barnola JM, Chappellaz J, Fischer H, Gallet JC, Johnsen S, Leuenberger M, Loulergue L, Luethi D, Oerter H, Parrenin F, Raisbeck G, Raynaud D, Schilt A, Schwander J, Selmo E, Souchez R, Spahni R, Stauffer B, Steffensen JP, Stenni B, Stocker TF, Tison JL, Werner M & Wolff EW, Orbital and Millennial Antarctic Climate Variability over the Past 800,000 Years, *Science* 2007, 317, 793–796, <https://doi.org/10.1126/science.1141038>.

Kaiser J, Lamy F & Hebbeln D, A 70-kyr sea surface temperature record off southern Chile (Ocean Drilling Program Site 1233), *Paleoceanography* 2005, 20, 2005PA001146, <https://doi.org/10.1029/2005PA001146>.

Lamy F, Kilian R, Arz HW, Francois J-P, Kaiser J, Prange M & Steinke T, Holocene changes in the position and intensity of the southern westerly wind belt, *Nat. geosci.* 2010, 3, 695–699, doi:10.1038/ngeo959.

Moreno PI, Kaplan MR, Francois JP, Villa-Martinez R, Moy CM, Stern CR & Kubik PW, Renewed glacial activity during the Antarctic cold reversal and persistence of cold conditions until 11.5 ka in southwestern Patagonia, *Geology* 2009, 37, 375–378, doi:10.1130/G25399A.1.

Moreno, PI, Videla J, Valero-Garcés B, Alloway BV & Heusser LE, A continuous record of vegetation, fire-regime and climatic changes in northwestern Patagonia spanning the last 25,000 years, *Quaternary Science Reviews* 2018, 198, 15–36. <https://doi.org/10.1016/j.quascirev.2018.08.013>.

Pedro JB, Bostock HC, Bitz CM, He F, Vandergoes MJ, Steig EJ, Chase BM, Krause CE, Rasmussen SO, Markle BR & Cortese G, The spatial extent and dynamics of the Antarctic Cold Reversal, *Nature Geosci.* 2016a , 9, 51–55, <https://doi.org/10.1038/ngeo2580>.

Perren B, Kaiser J, Arz H, Dellwig O, Hodgson D & Lamy F, Poleward displacement of the Southern Hemisphere Westerlies in response to Early Holocene warming, *Communications Earth & Environment*. 2025, 6. [10.1038/s43247-025-02129-z](https://doi.org/10.1038/s43247-025-02129-z).

Stöcker M, 2025, Authigene Mangankarbonatbildung in holozänen Sedimenten des hypoxisch/anoxischen Fjordsystems Golfo Almirante Montt in der patagonischen Fjordregion, Südchile, BSc-thesis, Univ. Greifswald.

Scientific Output

List of Publications

Kaiser J, Lamy F, Lange CB & Arz HW, Air temperature and rainfall variability in south-western Patagonia (52°S) during the Antarctic Cold Reversal and the Holocene, *Palaeogeography, Palaeoclimatology, Palaeoecology*, submitted.

Piret L, Bertrand S, Moffat C, Feldens P, Papenmeier S & Arz H, Recent ice-contact delta formation in front of Pio XI glacier controls sedimentary processes in Eyre Fjord, Patagonia, *Earth Surface Processes and Landforms* 2024, 1–15, DOI: [10.1002/esp.6012](https://doi.org/10.1002/esp.6012).

Krug AS & Zettler ML, Macrozoobenthic communities in the upwelling area off Chile (36°S) with special consideration of the oxygen minimum zone, *Diversity* 2025, 17, 278, doi: [10.3390/d17040278](https://doi.org/10.3390/d17040278).

Schmale O, Mohrholz V, Papenmeier S, Jürgens K, Blumenberg M, Feldens P, Jordan S, Ruiz-Fernández P, Meeske C, Fabian J, Iwe S & Umlauf L, The control of physical and biological drivers on pelagic methane fluxes in a Patagonian fjord (Golfo Almirante Montt, Chile), *Sci. Total Environ.* 2025, 982, 179584, doi: [10.1016/j.scitotenv.2025.179584](https://doi.org/10.1016/j.scitotenv.2025.179584).

Zettler ML, First record of the genus *Cardiomya* (Mollusca, Bivalvia, Cuspidariidae) off the Chilean margin and description of a new species, *Iberus* 2025, 43(2), 163–170, doi: 10.5281/zenodo.16988331.

Zettler ML, Re-establishment of *Malletia sorrow* (Soot-Ryen, 1957), an endemic bathyal bivalve off Chile (Mollusca: Bivalvia: Nuculanoidea), *Gayana* 2024, 88(2), 320–326, doi: 10.4067/S0717-65382024000200320.

List of conference presentations

2025 | **The control of physical and biological drivers on pelagic methane fluxes in a Patagonian fjord (Golfo Almirante Montt, Chile)** EGU, Vienna, Austria.

2025 | **Recent history of sedimentation in the Golfo Almirante Montt, southern Patagonian fjord system (52° S)** Workshop Fjords in a changing climate, Stalheim, Norway.

Data

Multibeam bathymetry raw data (Kongsberg EM 122 entire dataset) of RV SONNE during cruise SO296/2 [dataset]:
PANGAEA, <https://doi.org/10.1594/PANGAEA.968532>

Water column raw data (Kongsberg EM 122 entire dataset) of RV SONNE during cruise SO296/2 [dataset]:
PANGAEA, <https://doi.org/10.1594/PANGAEA.969117>

Multibeam bathymetry raw data (Kongsberg EM710 entire dataset) of RV SONNE during cruise SO296/2 [dataset]:
PANGAEA, <https://doi.org/10.1594/PANGAEA.968530>

Water column raw data (Kongsberg EM710 entire dataset) of RV SONNE during cruise SO296/2 [dataset]:
PANGAEA, <https://doi.org/10.1594/PANGAEA.968531>

Data from Schmale et al. (2025):
The raw geological data is available online at <https://doi.org/10.1594/PANGAEA.968531> (MBES) and <https://doi.org/10.12754/data-2024-0015> (parasound, Schulz-Vogt et al., 2024). The collection of hydrographic data used in this study are available via <https://doi.org/10.12754/data-2024-0020>. Detailed data from gas chemical and microbiological water column studies is available online at

<https://dx.doi.org/10.12754/data-2024-0022-01>. Amplicon and metagenomic sequencing data for this study have been deposited in the European Nucleotide Archive (ENA) at EMBL-EBI, using the data brokerage service GFBio (Diepenbroek et al., 2014), under INSDC accession number PRJEB82688.

Biological data, macrozoobenthic species, abundance and biomass along the transect: <https://www.mdpi.com/article/10.3390/d17040278/s1>.

Cruise report

SO296: https://dx.doi.org/10.48433/cr_so296_2

SO297

Expedition SO297(PISAGUA): Controlled-source seismic experiments offshore the Atacama Seismic Gap to elucidate structural controls on megathrust slip

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

D. Lange, A. Warwel, A. Dannowski, I. Klaucke, H. Kopp

Universidad de Chile | Santiago de Chile, Chile

E. Contreras-Reyes

Pontificia Universidad Católica de Valparaíso | Valparaíso, Chile

J. Díaz-Naveas

Pontificia Universidad Católica de Chile | Santiago de Chile, Chile

M. Moreno

Introduction

The northern Chilean margin is one of the most seismically active subduction zones, with a high potential for future megathrust earthquakes. The tectonic structure and the state of hydration of the incoming Nazca Plate, and their control on seismogenesis, are poorly known, as the offshore domain remains largely unexplored. The main objective of the ongoing PISAGUA project is a detailed high-resolution model of the marine forearc in Northern Chile, focusing on two working areas (Figure 1).

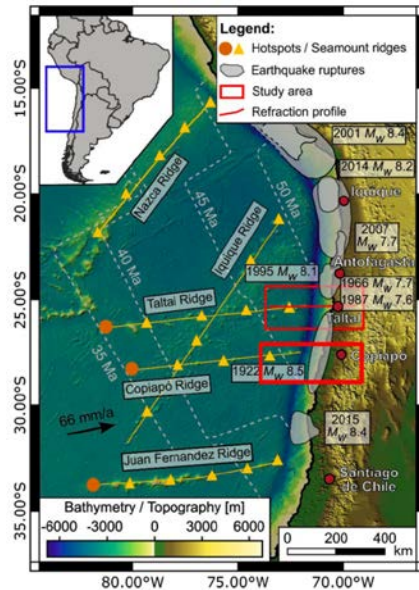


Figure 1: Map of the Chilean subduction zone. Gray areas indicate co-seismic slip of large earthquakes. Seamount ridges and their respective hotspots are marked by triangles and circles (modified after Warwel et al., under review).

The northern working area covers the Taltal ridge at $\sim 25^\circ\text{S}$, and the southern profile is parallel to the subducted Copiapó Ridge ($\sim 27^\circ\text{S}$) (Figure 1). Because North Chile is known for its high-level seismic activity related to mining activity, we extended the marine refraction profile onshore by using 23 geophones installed by GEOMAR (GIPP loan SO297-land) and 30 from Instituto Milenio de Oceanografía (IMO). The land stations were used to locate mine blasts, airgun shots, and seismicity to spatially extend the study to the onshore domain.

During the cruise, 42 ocean bottom seismometers and hydrophones from the GEOMAR pool were deployed several times, adding to a total of 115 times for two seismic refraction profiles and one 3D experiment. Furthermore, IMO and GEOMAR installed five novel drift-free pressure sensors (A-0-A type) to resolve subsidence and sea-level changes with a precision better than 1 cm for over five years (Lange et al. 2023). Two pressure sensors were deinstalled in January 2025, and the remaining three sensors will register until 2027.

Hydration and Intra-slab Seismicity at Taltal ($\sim 25^\circ\text{S}$), Summary of Warwel et al. (under review)

The incoming plate is characterized by E-W, trench-perpendicular oriented horst and graben structures cross-cut by N-S oriented, bending-related normal faults

Seamount Subduction and Slab Geometry at Copiapó (~27°S), Summary of Warwel et al. (2025)

Farther south, the Copiapó Ridge (Figure 3), a chain of volcanic seamounts formed ~10 Ma ago, is subducting below the South American continent. Amphibious refraction profiles, complemented by multibeam bathymetry, image five large seamounts with different morphologies. Some seamounts are conical, others stellate, with landslide scars, gullies, and small volcanic cones on their flanks.

The velocity model reveals slightly slower crustal velocities within seamounts (linked to extrusive volcanism), but locally higher velocities at their bases, interpreted as magmatic underplating. The uppermost mantle shows marked heterogeneity: while some areas exhibit velocities near 8 km/s, others are significantly reduced (~7.4–7.6 km/s), consistent with fracturing and hydration from bending faults. Slab geometry is equally revealing: instead of an abrupt steepening, as seen at 22°S (Contreras-Reyes et al., 2012), the Copiapó segment subducts smoothly, dipping ~12° down to a depth of about 25 km. The oceanic crust between seamounts is ~6–7 km thick, typical for 45 Ma Nazca lithosphere, but thickens to >10 km beneath the largest edifices.

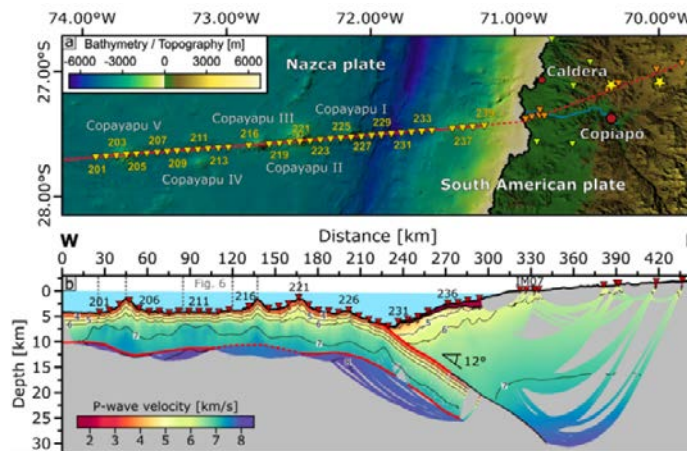


Figure 3: Map (a) and v_p velocity model (b) of the working area at latitudes of Copiapó city (Warwel et al., 2025).

Seismicity recorded by the land stations further refines this picture. Nearly 8,000 events were detected in six months. Hypocenters cluster in three distinct bands parallel to the slab: (1) along the subduction interface, (2) near the subducted oceanic Moho, and (3) in a deeper double Benioff zone ~20 km below the interface. The largest event during the deployment, a Mw 5.9 earthquake in April 2023, nucleated at ~54 km depth in the deepest band, followed by a classic aftershock decay sequence. Along the interface, seismicity is concentrated

in highly locked areas, while zones of low locking coincide with previously observed slow slip events (Klein et al., 2023). These observations demonstrate how seamount subduction influences coupling, segmentation, and the balance between seismic and aseismic slip.

Onshore instrumentation related to SO297

To extend the refraction profile to the onshore domain, we installed 23 geophones onshore and used another 30 temporary geophones from IMO (Figure 4). A total of 7,616 events (Figure 4) with more than 8 arrivals were located within. Considering the slightly curved trench, the events were located within a quasi-3D model by transposing the 2D P-wave velocity model from the refraction tomography. The seismicity and blasts extended the refraction profile onshore (Figures 2 and 3). The land stations were used with ~150 other stations to create a high-resolution earthquake catalogue with 165,000 events within 3.5 years (Münchmeyer et al., 2025).

Broader Significance

When viewed together, the Taltal and Copiapó studies outline the dual controls on seismicity in the Atacama gap. At ~25°S, bending-related faults allow fluids to penetrate deep into the lithosphere, promoting serpentinization and intra-slab seismicity. At ~27°S, seamount subduction thickens the crust, perturbs slab geometry, and creates asperities and barriers that modulate earthquake rupture. Both processes emphasize the central role of fluids in weakening the lithosphere, altering stress states, and shaping earthquake occurrence. Onshore geodetic data show that the Atacama margin remains strongly coupled (González-Vidal et al., 2023), suggesting the potential for a future Mw 8–8.5 rupture. Yet, the coexistence of hydrated mantle (favoring intermediate-depth seismicity) and subducted seamounts (fragmenting the interface) suggests that rupture behavior may be complex, possibly segmented or accompanied by slow slip. These factors offer a richer framework for understanding earthquake processes of the Atacama seismic gap.

Many subduction zones worldwide combine outer-rise faulting with seamount subduction, including Japan, Tonga, and Central America regions. These results advance our understanding of how fluids are distributed in the oceanic crust and mantle and their influence on seismicity and fluid pathways. They also highlight the power of amphibious, multidisciplinary experiments imaging subduction zone structure across the coastline. In summary, the studies demonstrate that the Atacama gap is not a “quiet” margin segment but a tectonically dynamic system where hydration, serpentinization, and seamount subduction jointly govern slab structure and seismicity.

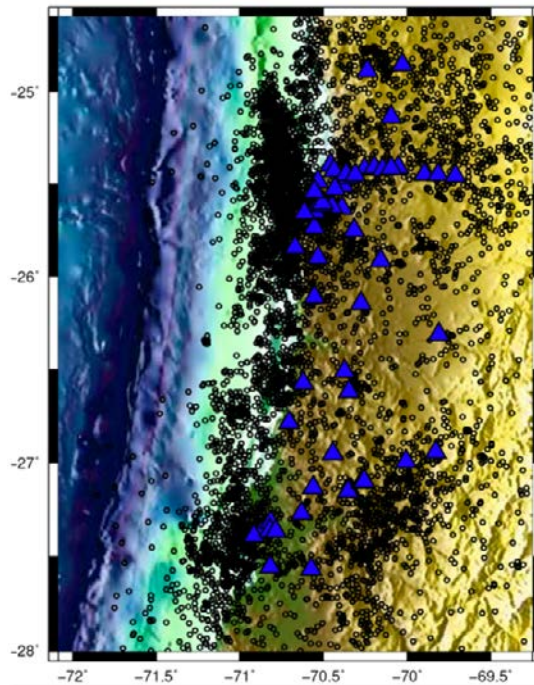


Figure 4: Seismicity located with the IMO and GEOMAR land stations.

References

Contreras-Reyes E, Jara J, Grevemeyer I, Ruiz S & Carrizo D, Abrupt change in the dip of the subducting plate beneath north Chile, *Nature Geoscience* 2012, 5(5), 342–345.

González-Vidal D, Moreno M, Sippl C, Báez J. C, Ortega-Culaciati F, Lange D, et al., Relation between oceanic plate structure, patterns of interplate locking and microseismicity in the 1922 Atacama seismic gap, *Geophysical Research Letters* 2023, 50, e2023GL103565.

Klein E, Vigny C, Duputel Z, Zigone D, Rivera L, Ruiz S & Potin B, Return of the Atacama deep slow slip event: The 5-year recurrence confirmed by continuous GPS, *Physics of the Earth and Planetary Interiors* 2023, 334, 106970.

Münchmeyer J, Molina-Ormazabal D, Marsan D, Langlais M, Baez JC, Heit B, González-Vidal D, Moreno M, Tilmann F, Lange D & Socquet A, Characterizing the Atacama Segment of the Chile Subduction Margin (24°S–31°S) With >165,000 Earthquakes, *Journal of Geophysical Research: Solid Earth* 2025, 130, e2025JB031256, doi: 10.1029/2025JB031256.

Warwel A, Lange D, Dannowski A, Contreras-Reyes E, Klaucke I, Diaz-Naveas J, Moreno M & Kopp H, Seismic Structure and Tectonics of the North-Central Chilean Subduction Zone Along the Copiapó Ridge From Amphibious Seismic Refraction Tomography and Local Seismicity, *Geochemistry, Geophysics, Geosystems* 2025, 26, e2024GC011829, doi: 10.1029/2024GC011829.

Warwel A, Lange D, Dannowski A, Klaucke I, Contreras-Reyes E, Moreno M, Diaz-Naveas J & Kopp H, Fault-induced hydration and serpentinization of the incoming lithosphere enhances intra-slab seismicity offshore Taltal (~25°S), Northern Chile, *Journal of Geophysical Research: Solid Earth* (under review).

Yáñez-Cuadra V, Ortega-Culaciati F, Moreno M, Tassara A, Krumm-Nualart N, Ruiz J, et al., Interplate coupling and seismic potential in the Atacama Seismic Gap (Chile), *Geophysical Research Letters* 2022, 49(11), e2022GL098257.

Scientific Output

List of Publications

Publications using the marine data of SO297

Warwel A, Lange D, Dannowski A, Contreras-Reyes E, Klaucke I, Diaz-Naveas J, Moreno M & Kopp H, Seismic Structure and Tectonics of the North-Central Chilean Subduction Zone Along the Copiapó Ridge From Amphibious Seismic Refraction Tomography and Local Seismicity, *Geochemistry, Geophysics, Geosystems* 2025, 26, e2024GC011829, doi: 10.1029/2024GC011829.

Warwel A, Lange D, Dannowski A, Klaucke I, Contreras-Reyes E, Moreno M, Diaz-Naveas J & Kopp H, Fault-induced hydration and serpentinization of the incoming lithosphere enhances intra-slab seismicity offshore Taltal (~25°S), Northern Chile, *Journal of Geophysical Research: Solid Earth* (under review).

Publications related to land stations:

González-Vidal D, Moreno M, Sippl C, Baez JC, Ortega-Culaciati F, Lange D, Tilmann F, Socquet A, Bolte J, Hormazabal J, Langlais M, Morales-Yáñez C, Melnick D, Benavente R, Münchmeyer J, Araya R & Heit B, Relation Between Oceanic Plate Structure, Patterns of Interplate Locking and Microseismicity in the 1922 Atacama Seismic Gap, *Geophysical Research Letters* 2023, 50, e2023GL103565, doi: 10.1029/2023GL103565.

Münchmeyer J, Molina-Ormazabal D, Marsan D, Langlais M, Baez JC, Heit B, González-Vidal D, Moreno M, Tilmann F, Lange D & Socquet A, Characterizing the Atacama Segment of the Chile Subduction Margin (24°S–31°S) With >165,000 Earthquakes, *Journal of Geophysical Research: Solid Earth* 2025, 130, e2025JB031256, doi: 10.1029/2025JB031256.

Hernández-Soto N, Sippl C, Miller M, Lange D, Tilmann F, González-Vidal D, Socquet A & Moreno M, Structure of the North-Central Chile subduction zone from local earthquake tomography, *Journal of Geophysical Research: Solid Earth*, under revision.

List of conference presentations

2025 | **Investigating the Atacama Seismic Gap within the North Chilean Subduction Zone**, GEOMAR Center Evaluation, Kiel, Germany.

2025 | **Combining Amphibious Seismic Refraction Data with Local Seismicity to Investigate the Structure and Geometry of the Chilean Subduction Zone in the South Atacama Region (25°–27.8° S)** SZ4D Ocean Technology workshop, Santiago de Chile, Chile.

2024 | **Combining Amphibious Seismic Refraction Data with Local Seismicity to Investigate the Structure and Geometry of the Chilean Subduction Zone in the South Atacama Region (25°–27.8° S)**, AGU Fall Meeting 2024, Washington D.C., United States of America

2024 | **Structure and geometry of the Chilean subduction zone near Copiapó (~27°S)**, IPOC meeting, Potsdam, Germany

2024 | **Structure and geometry of the Chilean subduction zone near Copiapó (~27°S) based on an amphibious seismic refraction experiment**, EGU General Assembly 2024, Vienna, Austria.

Data

Data of the refraction profile offshore Copiapó (~27.5°S):

Shots on OBS Data:

<https://doi.pangaea.de/10.1594/PANGAEA.969150>

Shots on OBH Data:

<https://doi.pangaea.de/10.1594/PANGAEA.969551>

Shots on seismological land stations:
<https://doi.pangaea.de/10.1594/PANGAEA.969552>

Multibeam bathymetry:
<https://doi.org/10.5281/zenodo.12783434>

Earthquake catalogue based on land stations:
<https://doi.org/10.5281/zenodo.13310788>

Continuous seismological data:
<https://gipp.gfz-potsdam.de/projects/view/794>

Data of the working area offshore Taltal (21°S):

The active source OBS, OBH and land seismometer data used to derive the P- and S-wave 2D refraction profiles are available in the Pangea data repository:

<https://doi.pangaea.de/10.1594/PANGAEA.984419>

<https://doi.pangaea.de/10.1594/PANGAEA.984420>

<https://doi.pangaea.de/10.1594/PANGAEA.984421>

Multibeam bathymetry:

<https://doi.org/10.5281/zenodo.16361774>

Cruise Report

SO297: https://doi.org/10.48433/cr_so297

SO289 and SO298

GEOTRACES section studies on trace element biogeochemistry in the South and Equatorial Pacific Ocean

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

N.D. Singh, E.P. Achterberg, B. Liguori, K. Gosnell, Z. Zhang, M. Frank

Constructor University | Bremen, Germany

A. Koschinsky, S. Pöhle

Motivation

The South and Equatorial Pacific Ocean (SPO and EPO, respectively) represent contrasting surface macronutrient (e. g., phosphate, nitrate, silicate) and primary productivity regimes in the ocean, varying from an ultra-oligotrophic and low-productivity region of the South Pacific Subtropical Gyre (SPSG) to a high-nutrient and high-productivity upwelling region of eastern Equatorial Pacific. The EPO is one of the major upwelling regions in the global ocean with strong outgassing of CO₂, while large areas of the SPO act as an important atmospheric CO₂ sink (Takahashi et al., 1997). The SPO and EPO, therefore, are crucial players in the global carbon cycle and show strong coupling between primary production and trace nutrient supply to the surface ocean (Christian et al., 2001). A low supply of Fe is shown to limit phytoplankton growth in the surface SPO and EPO (Browning & Moore, 2023). The current systems in the forms of large-scale anticyclonic gyre in the SPO, strong surface zonal currents along the EPO and deep Pacific western and eastern boundary currents play important roles in the global overturning circulation through their linkage with the Indonesian Through Flow (ITF) to the Indian Ocean and Antarctic Circumpolar Current (ACC) in the Southern Ocean. Furthermore, EPO and SPO hosts important topological features including the East Pacific Rise (EPR), a fast-spreading mid oceanic ridge, and the sub-marine volcano, the Hunga Tonga-Hunga Ha'apai, which may influence the trace element biogeochemistry of the SPO and EPO through the interaction of magmatic and hydrothermal fluids with seawater. In view of key controls of

trace nutrient availability on SPO and EPO surface primary productivity and the potential of trace elements as proxies of biogeochemical processes, there is a need to understand the processes that set the input and removal fluxes of trace element in these regions. We collected seawater and particulate samples along the German GEOTRACES cruise transects, GP21 (SO289) and GP11 (SO298), in the SPO and EPO, respectively. The study aims to establish the distributions of trace elements and their isotopes (TEIs), quantify their sources from the four major ocean boundaries (rivers, atmosphere, exchange with sediments, ocean crust), and determine their biogeochemical cycling and relationships to surface primary productivity and large-scale ocean circulation along the cruise transects.

Sampling

At each station, we sampled the full water column with a titanium GEOMAR CTD (Ti-CTD) for contamination prone variables (e. g., Fe, Zn), and using a stainless steel GEOMAR CTD (SS-CTD) for less contamination prone variables, including Rare Earth Elements (REEs) and isotopes of Nd and Th. An additional SS-CTD (BIO-CTD) was deployed to about 250-300 m depth at selected stations for collection of biological variables (e. g., phytoplankton abundance and composition, nitrogen fixation). The Ti-CTD and SS-CTD consisted of 24 Niskin bottles (Ocean Test Equipment; capacity: 10–12 L), mounted on a rosette frame and deployed to the ocean using dedicated hydrowire. Sub-sampling for the contamination prone trace elements in dissolved and particulate phases was achieved by transferring the Niskin bottles to class-100 clean room container. In addition, high-resolution surface seawater sampling was conducted using trace metal clean tow fish sampler every three hours during the cruise transits, and before approaching each station. We also sampled the Niskins from the SS-CTD for helium isotopes which we will use as a tracer of the hydrothermal fluid inputs to the ocean. Helium is a conservative tracer and allows us to follow the plume and determine the fluxes of elements.

The in-situ pumps were deployed to filter large seawater volumes (~150–2000 L) and collect particles for geochemical and biological investigations. Particulate Th isotopes (Th 234) obtained from the filters of the in-situ pumps were measured on-board. In addition, a Mn cartridge was placed on a number of the in-situ pumps, which allowed for the collection of long-lived Ra samples.

The PM10 dry aerosol fraction was sampled along the cruise transects using high volume aerosol collector (MCV CAV-A/Mb). We employed Whatmann 41 filter (acid-cleaned, 203 mm x 254 mm) for trace elements and isotope sampling. Filters were changed every 48–72 h, and stored frozen (–20 °C).

Selected results and interpretations

Overall, dissolved trace nutrients (Fe, Co, Ni, Cu, Zn, Cd) showed minima in the surface waters (<100 m) of the SPO and EPO, indicating phytoplankton uptake and low atmospheric supply. In the EPO, trace nutrients including Ni, Cd, Zn and Cu, together with macronutrients (NO_x, P, Si), showed strong horizontal gradients in the upper 300 m and were apparent as eastward shoaling of concentration isolines, similar to the Equatorial Undercurrent (EUC) core and temperature isolines. This indicates the important role of vertical upwelling for the supply of trace metals to the surface EPO, where the west-east transport of cold, nutrient-rich sub-surface waters by the EUC influences the vertical trace nutrient fluxes. In the sub-surface waters (>200 m) of the SPO and EPO, dissolved trace nutrient distributions showed overall increases, which were influenced by water masses mixing and remineralization of sinking organic matter (OM).

Investigation of Cu-binding organic ligands (LCu) revealed the presence of strong ligands throughout the water column along both the cruise transects but were slightly weaker on average for the SPO (logK range: ~10–13) than for the EPO (logK range: ~11–14). No notable trends were observed in ligand concentrations or stability constants between stations, and free Cu²⁺ (unbound to ligands) remained below potentially toxic concentrations. Concentrations of dissolved Cu and LCu were largely similar between different size fractions (10 kDa, 0.015 µm, 0.2 µm and 0.8 µm), indicating that most Cu and ligands were present in the smallest size fraction.

The distribution of high field strength trace elements including Zr and Hf showed enrichment in deeper waters, which may reflect release from sinking particulate material or the influence of deep-water circulation. The distributions of Zr, Hf, and the Zr/Hf ratio show strong positive correlations with silicate suggesting a close link to remineralization processes or water mass transport and mixing trends similar to silicate. The observed Zr/Hf ratio trends imply fractionation processes probably associated with particle scavenging or sediment–water interactions.

The chemical speciation of redox-sensitive trace elements, Cr and V, in seawater is strongly influenced by the dissolved oxygen (DO) concentration. Results indicate the influence of low dissolved oxygen (DO) in oxygen minimum zone (OMZ) on relative distributions of Cr³⁺ and Cr⁶⁺, more pronounced in the coastal waters of the SPO than the EPO waters due to the extensive mixing under the influence of EUC. Preliminary data on sequentially filtered samples suggest that Cr is mostly present in the soluble phase (< 0.02 µm). Although V(V) was the dominant redox species throughout the entire profiles (16.8–36.6 nmol/kg), V(IV) was also detected (0.9–3.2 nmol/kg). In general, the concentration of V(IV) decreases with the depth in the photic zone in the upwelling regions while it remains constant in deeper waters. Furthermore, an increase in both V(V) and V(IV) was observed

with decreasing DO in the coastal upwelling regions, which is likely due to the release of V redox species during the degradation of organic matter in the OMZ. The results obtained indicated that V redox species are not controlled by DO, but scavenging and biological activities are considered as key factors of V redox speciation.

We studied the biogeochemical cycling of Ba in the EPO given its close link with the marine carbon cycle as particulate barite (BaSO_4) forms during the oxidation of sinking organic matter. The elemental and isotopic composition of Ba in the dissolved and particulate phase is examined to understand relative roles of *in situ* BaSO_4 precipitation and large-scale water mass mixing on Ba distribution. Overall, dissolved Ba (dBa) and its isotopic composition ($\delta^{138}\text{Ba}$) showed consistent patterns along the EPO with low dBa and a heavier $\delta^{138}\text{Ba}$ signature in surface waters, and high dBa and lighter $\delta^{138}\text{Ba}$ signature at depths. These distribution patterns indicate passive uptake of Ba by phytoplankton in the surface waters, while the BaSO_4 formation was important in intermediate waters. Below the Intermediate waters, $\delta^{138}\text{Ba}$ remained relatively uniform, indicating absence of or slow BaSO_4 remineralization and a role of water mass mixing and advection in governing Ba distribution. At depths below 2000 m, dBa showed deviation from conservative behavior in the eastern EPO, presumably due to benthic input. The dBa, pBa and their isotopic composition showed no significant correlation with surface Chl-a concentrations, suggesting the formation of BaSO_4 in the EPO is not directly related to biological production. Overall, the results suggest that Ba cycling is primarily governed by the large-scale water mass mixing and upwelling with secondary role of biological and benthic processes.

The GP21 (SO298) cruise took place (February–April 2022) following the January 2022 eruption of the Hunga Tonga-Hunga Ha’apai (HTHH) volcano, discharging 2,900 teragrams of ejecta, majority of which was deposited in the SPSG. The impact of the deposited volcanic matter on the biogeochemistry of SPSG was examined using the distributions of Nd isotopes, REEs and trace metals (Fe, Mn, Al). The Nd isotopic signature and REEs pattern in the surface waters showed prominent volcanic impact in the western SPSG. In the euphotic waters, east-west increases in trace metal (Al, Mn, Fe) concentrations together with chlorophyll-a inventories were observed, suggesting the supply of trace nutrients to the surface SPO following the deposition of volcanic ejecta, which triggered a biological response. Flux estimates indicated deposition of up to 0.16 kt of Nd and 32 kt of Fe to the SPSG following the volcanic eruption, comparable to the annual global Nd dust flux and annual dust flux of Fe to the entire SPSG. The radiogenic isotope composition of Nd (ϵNd) is also determined over the full water column along the GP21 transect to understand the relative roles of water mass mixing and processes including boundary exchange, benthic fluxes and hydrothermal inputs on ϵNd in the Pacific interior. The estimates of fractions of water masses contributing to the water column, derived using an Optimum Multi-Parameter Analysis, were used to

show that ϵNd and Nd could largely be explained by conservative water mixing with non-conservative behavior restricted close to the western and eastern SPO boundaries. Importantly, we show that ϵNd of the Lower Circumpolar Deep Water is not altered by benthic fluxes as it travels northward from sub-polar South Pacific to $\sim 20^\circ\text{S}$. This study has implications for the use of ϵNd as a tracer of paleo-ocean circulation in the central SPO and boundary Nd exchange.

References

Browning TJ & Moore CM, Global analysis of ocean phytoplankton nutrient limitation reveals high prevalence of co-limitation, *Nature Communications* 2023, 14, 5014. doi:10.1038/s41467-023-40774-0.

Christian JR, Verschell MA, Murtugudde R, Busalacchi AJ & McClain CR, Biogeochemical modelling of the tropical Pacific Ocean. I: Seasonal and interannual variability, *Deep Sea Research Part II: Topical Studies in Oceanography* 2001, 49(1-3), 509-543. doi:10.1016/S0967-0645(01)00110-2.

Takahashi T, Feely RA, Weiss RF, Wanninkhof RH, Chipman DW, Sutherland SC & Takahashi TT, Global air-sea flux of CO_2 : An estimate based on measurements of sea-air pCO_2 difference, *Proceedings of the National Academy of Sciences* 1997, 94(16), 8292-8299. doi: 10.1073/pnas.94.16.8292.

Scientific Output

List of Publications

Guo JA, Strzepek RF, Yuan Z, Swadling KM, Townsend AT, Achterberg EP, Browning TJ & Bach LT, Effects of ocean alkalinity enhancement on plankton in the Equatorial Pacific, *Open Access Communications Earth & Environment* 2025, 6 (270), doi: 10.1038/s43247-025-02248-7.

Zhang Z, Xu A, Hathorne E, Gutjahr M, Browning TJ, Gosnell KJ, Liu T, Steiner Z, Kiko R, Yuan Z, Liu H, Achterberg EP & Frank M, Substantial trace metal input from the 2022 Hunga Tonga-Hunga Ha'apai eruption into the South Pacific, *Open Access Nature Communications* 2024, 15 (1), doi: 10.1038/s41467-024-52904-3.

Liu H, Yuan Z, Gosnell KJ, Liu T, Tammen JK, Wen Z, Engel A, Liu X, Huang B, Kao SJ, Achterberg EP & Browning TJ, Patterns of (micro)nutrient limitation across the South Pacific Ocean, Open Access Communications Earth & Environment 2024, 5 (1), doi: 10.1038/s43247-024-01749-1.

List of conference presentations

2026 | **Chromium redox speciation in coastal oxygen minimum zones in the tropical and subtropical Pacific and Atlantic Oceans** Ocean Sciences Meeting, Glasgow, Scotland.

2025 | **Biogeochemical controls on dissolved zinc cycling in the Equatorial Pacific Ocean** EGU, Vienna, Austria

2025 | **Constraining the Equatorial Pacific barium cycle with stable barium isotopes** Goldschmidt Conference, Prague, Czech Republic

2025 | **Was it really chemistry all along? Resolving the factors that influence profiles and distributions of nutrient-like metals (Zn, Ni, Cu and Cd) in the South Pacific Ocean** Goldschmidt Conference, Prague, Czech Republic

2025 | **Evidence for anthropogenic zinc in the south Pacific Ocean (GEOTRACES GP21)** Goldschmidt Conference, Prague, Czech Republic

2024 | **Dissolved and Particulate Trace Metal Trials and Tribulations across the GEOTRACES GP21 South Pacific Ocean transect** Ocean Sciences Meeting, New Orleans, USA

2023 | **Investigating Volcanic Input and Water Mass Mixing in the Southwest Pacific Ocean using Radiogenic Neodymium Isotopes and Rare Earth Elements** Goldschmidt Conference, Lyon, France

Data

Mastertrack, SO289:
<https://doi.org/10.1594/PANGAEA.947850>

Mastertrack, SO298:
<https://doi.org/10.1594/PANGAEA.963244>

Continuous TSG data, SO289:
<https://doi.org/10.1594/PANGAEA.953836>

Continuous TSG data, SO298:

<https://doi.org/10.1594/PANGAEA.966342>

ADCP data, SO289:

<https://doi.org/10.1594/PANGAEA.946261> and

<https://doi.org/10.1594/PANGAEA.946319>

ADCP data, SO298:

<https://doi.org/10.1594/PANGAEA.963748> and

<https://doi.org/10.1594/PANGAEA.963747>

Surface water Nd isotopes, rare earth elements and trace metal
(Al, Mn, Fe) data, SO289:

<https://doi.org/10.1594/PANGAEA.971875>

Cruise Reports

SO289: https://doi.org/10.48433/cr_so289

SO298: https://doi.org/10.48433/cr_so298

SO299

DYNAMET – Arc rifting, metallogeny and microplate evolution: An integrated geodynamic, magmatic and hydrothermal study of the Bismarck Archipelago, Papua New Guinea

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

P.A. Brandl, L.-M. Gautreau, S.G. Sander, J. Wenske

GeoZentrum Nordbayern, Friedrich-Alexander University Erlangen-Nürnberg | Erlangen, Germany

J.J. Falkenberg, K.M. Haase, J. Wenske

Technische Universität Berlin | Berlin, Germany

J.J. Falkenberg

University of Helsinki | Helsinki, Finland

C. Beier

Expedition Overview

The SO299 DYNAMET expedition, conducted aboard the German research vessel *RV Sonne*, explored the links between geODYNAMics and METAllogeny in eastern Papua New Guinea. The expedition focused on three main areas (Figure 1): the New Ireland Basin with the Tabar-Lihir-Tanga-Feni (TLTF) island chain, the Weitin Fault south of New Ireland, and the Mussau Ridge to the north.

Over 4,800 kilometers of hydroacoustic and gravimetric surveys were conducted, twelve ROV KIEL 6000 dives were completed, and 16 video-guided grab stations were deployed. A diverse set of samples was collected, including 447 rock, 346 sediment, and 570 gas and fluid samples. Near Lihir Island, 18 Ocean Bottom Seismometers (OBS) and 16 Ocean Bottom Magneto-Telluric (OBMT) instruments

were deployed (Figure 1B). Selected gas (n=100), fluid (n=98), sediment (n=75), and rock samples (n=192) have been analyzed to date.

Here, we briefly report on the current state of the data analyses and interpretation and present the key scientific outcomes.

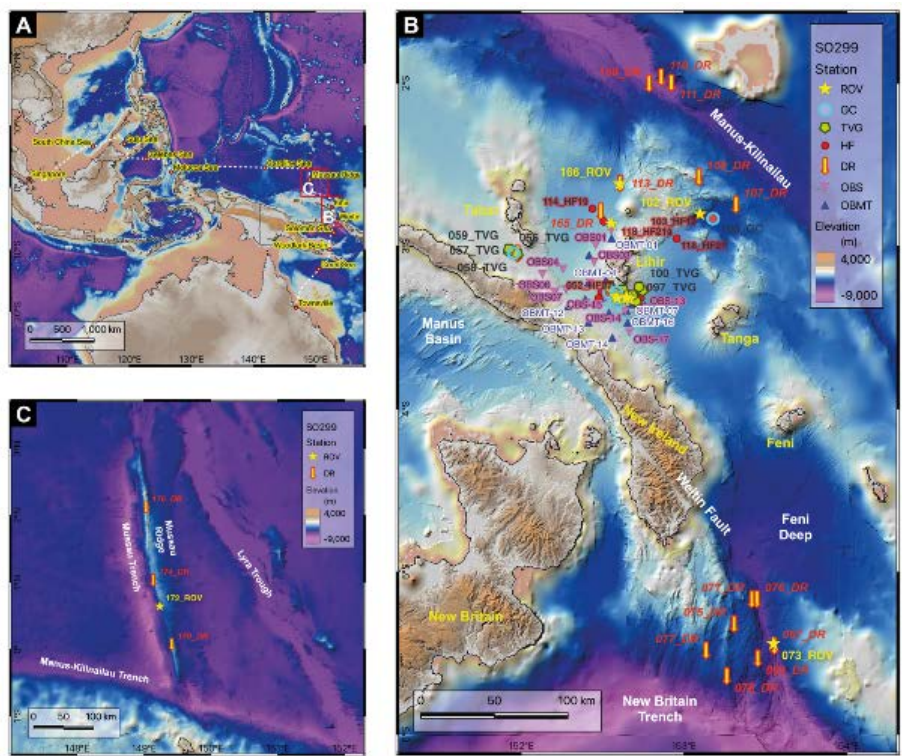


Figure 1: Overview maps. A) cruise track, B) TLTF island chain and Weitin Fault area, C) Mussau Ridge and Trench.

Discovery of the Karambusel Vent Field

During expedition SO299, the first deep-sea hydrothermal vent system along the TLTF chain was discovered at the Karambusel vent field. This system is hosted by a younger volcanic center on the western flank of the 287 ka-old Conical Seamount. Karambusel is unique in hosting both fossil high-temperature, gold-rich mineralization and an active low-temperature (<51°C) vent system (Figure 2). The hydrothermal fluids are derived from condensed magmatic vapor and/or connate fluids, and gas bubbles observed at some sites contain an unusually high proportion of methane with a thermogenic signature. This makes Karambusel the first globally recognized hybrid system combining magmatic-hydrothermal venting

and hydrocarbon seepage. The vent field supports chemosymbiotic fauna (Figure 2), with more endemic species identified than in nearby seeps, reflecting the distinct ecological niche created by the hybrid hydrothermal-hydrocarbon system. This discovery was recently presented to the scientific community in a publication by Brandl et al. (2025) in *Scientific Reports*.



Figure 2: Hydrothermal fluid vent and related faunal zones at the Karambusel vent field.

The Karambusel eruptive center formed 88.5 ka ago. Petrological and geochemical analyses show that Karambusel lavas are more hydrous than those of Conical Seamount, with adakite-like trace element signatures and abundant amphibole-phlogopite phenocrysts. These features indicate derivation from a metasomatized mantle source and shallow crustal storage. Pressure estimates confirm shallow magma stagnation, promoting volatile enrichment and fluid exsolution, crucial for Cu-Au porphyry-epithermal mineralization. Radiometric ages link the volcanism at Karambusel with epithermal Au-Ag mineralization at both Conical summit and Karambusel, suggesting magmatic rejuvenation triggered concurrent volcanic and mineralizing events. A related article by Gautreau et al. focusing on the Karambusel magmatic system is currently in preparation for *Journal of Petrology*.

Karambusel represents a unique Au-rich submarine epithermal system that shares similarities to the mineralization at the summit area of Conical Seamount. Detailed petrographic analyses, coupled with sulfide trace element and S isotope data, reveal the evolution and metal enrichment processes during mineralization. The primary mineralization consists of polymetallic sulfides within amorphous silica veins crosscutting altered ankaramite breccias. Gold occurs mainly as electrum

(20 μm grains) and in minor Au-rich orpiment, with bulk Au concentrations up to 28 $\mu\text{g/g}$. Magmatic fluids are the principal source of Au, while phase separation likely enhanced Au precipitation. Low-temperature As-Sb-Tl-Hg sulfides are associated with currently active venting of temperate, low-salinity fluids and methane seepage (>80% CH_4). Sulfur isotope variations (-21 to 4 ‰ for $\delta^{34}\text{S}$) indicate complex S cycling involving magmatic, biogenic, and methane-related processes. The related manuscript by Falkenberg et al. is in preparation for *Economic Geology*.

Evolution of K-rich magmatism

During SO299, two submarine volcanoes (Olpela Ples, Pikinini seamounts) were discovered during hydroacoustic surveys and the volcanic nature of these and several other seamounts was verified by sampling (dredge, video-guided grab, ROV). Among those are two volcanic centers south of Tabar that erupted the most primitive rocks known from the entire TLTF island chain. Other seamounts such as New World or Olpela Ples show a wide range of compositions from trachybasalt to trachyandesite. The primitive lavas and the processes that control magmatic differentiation are subject of ongoing research.

Crustal basement of the New Ireland Basin

Crustal xenoliths entrained in Quaternary high-K to shoshonitic lavas from submarine volcanoes provide insights into the composition of the crust beneath the New Ireland Basin and TLTF island chain. The studied xenoliths include basaltic, gabbroic, dioritic, granodioritic, and tonalitic lithologies, revealing a K-poor, tholeiitic crust with compositions ranging from mid-ocean ridge basalt (MORB)-like to arc-associated. Evidence for magma-wall rock interactions is present but some original signatures are preserved. Isotopic trends indicate a depleted mantle origin, consistent with an Indian MORB-type source. These results suggest that young K-rich arc magmatism developed above an older, K-poor arc-related crust, offering a rare glimpse into crustal evolution in a backarc environment. The study is currently in its final stages of preparation and will soon be submitted to *Journal of Petrology* by Wenske et al.

Geophysical surveys around Lihir

Magnetotelluric data from all valid stations were carefully pre-processed and processed to remove noise, offsets, and inconsistencies, using customized MATLAB tools and the BIRRP software to derive electromagnetic impedances. Multiple iterations were required, including adaptive segmentation and filtering,

to expand the usable frequency range (~90–20,000 s) and address hardware issues, improving data quality and consistency. Dimensionality analysis using TE/TM modes and Berdichevsky averages revealed a complex subsurface structure strongly influenced by topography and coastal effects, with high-conductivity anomalies in central and eastern areas and significant contrasts near New Ireland and the Lihir volcanic field. Strike angles and kappa values suggested mostly 3D structures. Building on this, a 3D inversion workflow was initiated using JIF3D, incorporating gridded bathymetry, resistivity start models, sediment layers, and iterative adjustments to achieve convergence. Preliminary inversions already highlighted central and eastern anomalies, and further refinement—particularly integrating sediment thickness from seismic data—promises improved resolution of shallow and deeper subsurface structures.

A total of 18 ocean-bottom seismometers (OBS) were deployed in the Lihir area for ~3 weeks, recording at 1000 Hz. All stations were successfully recovered, and time drifts for synchronized stations ranged from -85 to 184 ms. Manual inspection of vertical and hydrophone channels revealed no local earthquakes, only teleseismic and ~30 regional events at 180–240 km distance. The network was capable of detecting events with magnitude >1.5, and historical data indicate very low seismicity in the area (five crustal events up to M5.1 between 2010–2025).

Submarine extension of the Weitin Fault

The Weitin Fault is a translithospheric sinistral strike-slip fault with a rapid average motion rate of 130 mm/a (Brandl et al., 2024). The fault cuts through the southernmost portion of New Ireland and runs southwards towards a triple junction with the New Britain Trench. During SO299, this submarine portion of this highly seismogenic zone (historic M_w 8.0 events) was mapped for the first time using modern hydroacoustic methods. Additional ground-truthing by ROV revealed first insights into the nature and structure of this major fault zone. A related BSc thesis was finished by Frey at the University of Bonn.

The Mussau Ridge – an incipient of failed subduction zone?

The Mussau Ridge and Trench, located between Papua New Guinea and the Federated States of Micronesia, represents a type locality for induced subduction initiation. Expedition SO299 mapped and sampled the ridge along its entire length, focusing on structural and lithological variations. Preliminary data indicate a depleted MORB-like crust, with exposed lavas (layer 2A) and sheeted dykes (layer 2B) of oceanic igneous crust. Structural mapping reveals a thrust system in the central segment, while the northern and southern portions display evidence for lateral shear. Recent trace element and Sr-Nd-Pb-Hf isotope analysis reveal a high compositional

variability. However, some of the lavas record a highly depleted geochemical signature. Radiometric ages obtained from whole-rock Ar-Ar dating show an age offset to magnetic ages of the Caroline Plate crust to the West of the Mussau Trench. We interpret the Mussau Trench and Ridge as a failed subduction zone (based on the lack of teleseismic events) that initially developed from a transform fault within the Caroline Plate. A related master thesis by Waßmund was finished in 2024 at the CAU.

References

Brandl PA, Sander SG, Beier C, Schmidt M, Falkenberg JJ, Kihara T, et al., Coupled hydrothermal venting and hydrocarbon seepage discovered at Conical Seamount, Papua New Guinea. *Scientific Reports* 15, 32389, doi: 10.1038/s41598-025-17192-x.

Brandl PA, Hannington MD, Krätschell A, Petersen S, Baxter AT, Stewart MS, et al., A New Geological Map of the Marginal Basins of Eastern Papua New Guinea: Implications for Crustal Accretion and Mineral Endowment at Arc–Continent Collisions, *Lithosphere* 2024, lithosphere_2024_145, doi: 10.2113/2024/lithosphere_2024_145.

Scientific Output

List of Publications

Brandl PA, Hannington MD, Krätschell A, Petersen S, Baxter AT, Stewart MS, et al., A New Geological Map of the Marginal Basins of Eastern Papua New Guinea: Implications for Crustal Accretion and Mineral Endowment at Arc–Continent Collisions, *Lithosphere* 2024, lithosphere_2024_145, doi: 10.2113/2024/lithosphere_2024_145.

Brandl PA, Sander SG, Beier C, Schmidt M, Falkenberg JJ, Kihara T, et al., Coupled hydrothermal venting and hydrocarbon seepage discovered at Conical Seamount, Papua New Guinea, *Scientific Reports* 2025, 15, 32389, doi: 10.1038/s41598-025-17192-x.

Falkenberg JJ, Brandl PA, Petersen S, Keith M, Hannington MD, Haase KM, Beier C, Scicchitano MR, Strauß H & Frische M, Gold and Sulfur cycling in the unique Karambusel vent field, Conical Seamount, PNG: A hybrid between magmatic-hydrothermal venting and cold seepage revealed by sulfide microanalysis, in preparation for *Economic Geology*.

Gautreau L-M, Hansteen TH, Portnyagin M, Beier C, Frische M & Brandl PA, Understanding the links between volcanic systems and epithermal ore formation: A case study from Conical Seamount, Papua New Guinea, *Lithos* 2024, 482–483, 107695. doi: 10.1016/j.lithos.2024.107695.

Gautreau L-M, Brandl PA, Hansteen TH, Beier C, Genske F, Schenk J, Segall Z & Sander SG, Rejuvenation of the magmatic system triggers epithermal mineralization – evidence from the Karambusel eruptive center at Conical Seamount, Papua New Guinea, in preparation for *Journal of Petrology*.

Wenske J, Brandl PA, Haase KM, Hansteen TH & Beier C, Arc above arc: xenolith evidence for tholeiitic Melanesian Arc crust underlying K-rich lavas in the New Ireland Basin, Papua New Guinea, in preparation for *Journal of Petrology*.

List of conference presentations

2024 | **The Mussau Ridge and Trench – news from an infant subduction zone.** EGU General Assembly 2024, Vienna, Austria.

2024 | **The importance of magmatic degassing at a mineralized, submarine volcano: The case of Conical Seamount, Papua New Guinea.** EGU General Assembly 2024, Vienna, Austria.

2024 | **Two months at sea: Insights in the SO299 DYNAMET Expedition with RV SONNE, Papua New Guinea, Western Pacific.** 8th GOOD Meeting, Freiberg, Germany.

2024 | **Au-rich submarine epithermal mineralization coupled to active hydrocarbon seepage at the Karambusel vent field, Conical Seamount, Papua New Guinea.** GeoSaxonia 2024, Dresden, Germany.

2024 | **The Mussau Ridge – news from and incipient subduction zone.** Sektionstreffen Petrologie und Petrophysik, Deutsche Mineralogische Gesellschaft, Karlsruhe, Germany.

2025 | **Endemic fauna and complex mineralization linked to combined venting and seepage at the Karambusel vent field, PNG.** Goldschmidt Prague 2025, Prague, Czech Republic.

2025 | **Gold and Sulfur cycling in the unique Karambusel vent field, Conical Seamount, PNG: A hybrid between magmatic-hydrothermal venting and cold seepage revealed by sulfide microanalysis.** Goldschmidt Prague 2025, Prague, Czech Republic.

Data

Master track of SONNE cruise SO299/1 in 1 sec resolution:

<https://doi.org/10.1594/PANGAEA.963992>

Master tracks in different resolutions of SONNE cruise SO299/1, Townsville – Singapore, 2023-06-07–2023-07-29:

<https://doi.org/10.1594/PANGAEA.963991>

Water column raw data (Kongsberg EM 122 entire dataset) of RV SONNE during cruise SO299:

<https://doi.org/10.1594/PANGAEA.968523>

Multibeam bathymetry raw data (Kongsberg EM 122 entire dataset) of RV SONNE during cruise SO299:

<https://doi.org/10.1594/PANGAEA.968523>

Shipboard ADCP current measurements (38 kHz) during RV SONNE cruise SO299:

<https://doi.org/10.1594/PANGAEA.966064>

Shipboard ADCP current measurements (75 kHz) during RV SONNE cruise SO299:

<https://doi.org/10.1594/PANGAEA.965941>

Continuous optical chlorophyll-a and turbidity data along R/V SONNE cruise SO299:

<https://doi.org/10.1594/PANGAEA.974881>

Continuous thermosalinograph oceanography along RV SONNE cruise track SO299/1:

<https://doi.org/10.1594/PANGAEA.968988>

Cruise Report

SO299: https://doi.org/10.48433/cr_so299

SO299/2

Landslide-induced caldera collapse during the 1883 Krakatau eruption

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

M. Urlaub, J. Karstens, C. Berndt, S. Kutterolf, J.C. Schindlbeck-Belo

GFZ German Research Centre for Geosciences | Potsdam, Germany

T. Walter

BRIN Badan Riset dan Inovasi Nasional | Bandung, Indonesia

S. Husrin, A. Nugroho, A. Pratama, S. Karima, S. Ardhyastuti

Introduction

One of the most disastrous eruptions and tsunamis in recorded history occurred in 1883 at Krakatau in the Sunda Strait between Sumatra and Java, Indonesia. The eruption was extraordinary because of its explosivity and the concurrent release of huge volumes of eruption material (25 km³), leading to the formation of a collapse caldera during the final stage. Prior to the 1883 eruption, Krakatau's edifice was 9 km long, 5 km wide and 820 m high, and consisted of three volcanic cones. Two-thirds of the island disappeared during the eruption. Multiple tsunamis occurred, culminating in one of the largest volcanic tsunamis in recorded history devastating the coasts of Java and Sumatra with up to 40 m high waves, resulting in more than 36,000 casualties. A large amount of contemporary literature summarizing eyewitness accounts, tide gauge and air pressure records are available for the Krakatau eruption. These observations and subsequent work built invaluable foundations of modern volcanology (Verbeek, 1884), and provided important milestones in volcanic tsunami research (Latter 1981, Paris 2015), as well as atmospheric and climate sciences (Robock 2001). Yet, there is still no consensus on the processes that led to the caldera-forming eruption nor the tsunami waves of up to 40 m preceding the destructive pyroclastic flows that reached the Sunda Strait coastlines hundreds of kilometers away. Understanding the formation mechanism of volcanogenic tsunamis is highly relevant to Krakatau's current activity, which resulted in a small but deadly tsunami as recently as 2018 (Walter et al., 2019).

Results and interpretation

During research cruise SO299/2 in August 2023, a marine geophysical and geological survey was conducted in the waters surrounding the Krakatau Archipelago. The survey yielded high-resolution bathymetric data gridded to 5 m spatial resolution (Figure 1 inset). The seafloor west, south and east of Krakatau is littered with lobe-shaped fields of hummocks, which are separated by flat areas. The most prominent hummock field is located to the west of the island of Sertung. Some of the hummocks are up to 300 x 300 m wide and, in some cases, rise up to 100 m above the surrounding seafloor. Their morphology is predominantly angular (Figure 1 inset) with internal structures being partially offset due to faulting as imaged in seismic data. These observations indicate that hummocks were behaving brittle, were deposited as a relatively cold material and had not been rounded by transportation process or erosion. The lobe-shape and hummock size distribution are typical for volcanic debris avalanches. Consequently, we interpret this hummock field to the west of Krakatau as a debris avalanche deposit and the hummocks as blocks of the former Krakatau volcano. Seismic imaging reveals internal stratification for the largest hummocks, which can be traced down to the pre-1883 seafloor, suggesting that the large hummocks were emplaced prior to the 15 to 30 m thick, well-stratified surrounding sediment. These sediments were directly sampled with gravity cores. The lowermost metres of the core are dominated by rhyolitic glass compositions, consistent with the 1883 Krakatau eruption. The lower parts of the cores have thus intersected the upper surface of the 1883 submarine deposits.

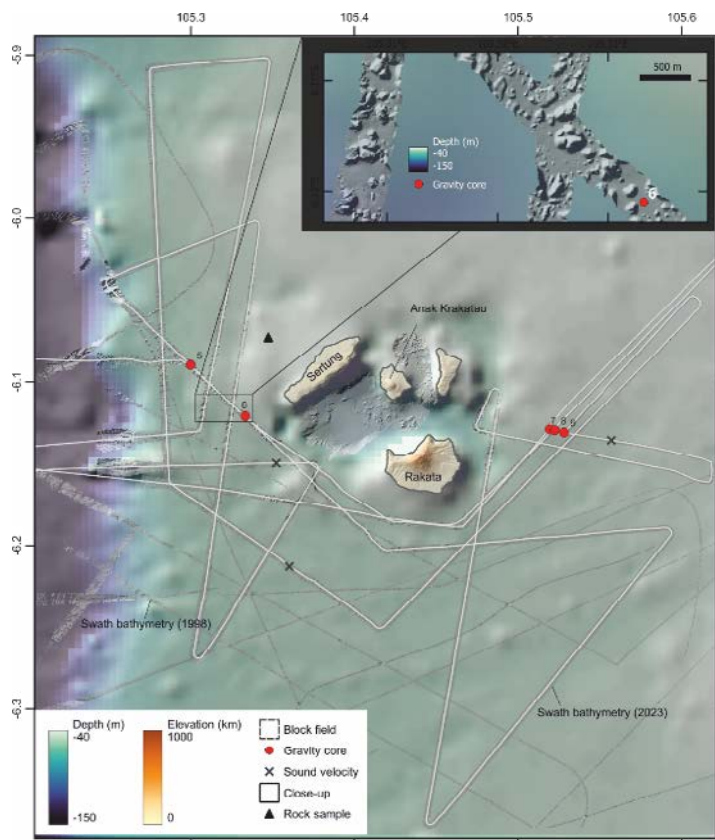


Figure 1: Shaded relief map of the surveyed area in the Sunda Strait, Indonesia. Compilation of bathymetric data acquired with the German research vessel RV SONNE during research cruises SO299/2 in August 2023, SO137 in 1998 (https://webapp-srv1a.awi.de/eBathy/cruise_info2.php?cruise=447), and GEBCO in the background. Swath bathymetry data within the archipelago and in the proximal north was acquired in 2019 (Hunt et al. 2021). Onshore topography is satellite-based (doi /10.5066/F7PR7TFT). Cruise track of SO299/2 along which swath bathymetry and seismic profiles were acquired is shown in white. The close-up in the upper right corner is a shaded relief map of the seafloor in the area of the debris avalanche deposit. The new swath bathymetry data collected with the EM710 system onboard RV SONNE clearly images the distinct blocks.

Discussion

We hypothesize that the only viable mechanism for the formation of the debris avalanche is a sector collapse of the Krakatau edifice. The collapse must have occurred prior to the deposition of the bulk erupted volume, which is deposited in between the collapse blocks. This deposit corresponds to the ignimbrite-forming phase of the eruption prior to caldera subsidence. The earliest possible collapse occurrence is half a day before the climactic phase, as eye witnesses reported the edifice to be still intact. The short timing between collapse and the transition into the caldera-forming eruption suggests a causative link. There are two ways in which a sector collapse impacts the eruption dynamics to foster

caldera formation: magmatic processes driving ascent, and the physical, surficial processes involved in caldera fault formation and subsidence. Both magmatic and structural mechanisms could act together to cause the eruption to shift from a normal, but intense, Plinian eruption to a caldera-forming event with the sector collapse being the initial trigger.

Conclusion

These results rewrite the series of events that led to the caldera-forming eruption of Krakatau in 1888 and show that a sector collapse was an important agent in the climactic eruption and tsunami. This requires a reassessment of volcano hazards where Krakatau was used as a benchmark.

References

Hunt JE, et al., Submarine landslide megablocks show half of Anak Krakatau island failed on December 22nd, 2018, Nat. Commun 2021, 12, 2827.

Latter JH, Tsunamis of volcanic origin: Summary of causes, with particular reference to Krakatoa, 1883, Bull. Volcanol. 1981, 44, 467–490.

Paris R, Source mechanisms of volcanic tsunamis, Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 2015, 373, 20140380.

Robock A, Volcanic eruptions and climate, Rev. Geophys. 2000, 38, 191–219.

Verbeek RDM, The Krakatoa Eruption 1, Nature 1884, 30, 10–15.

Walter TR, et al., Complex hazard cascade culminating in the Anak Krakatau sector collapse, Nat. Commun. 2019, 10, 4339.

Scientific Output

List of Publications

Urlaub M, Furst S, Schindlbeck-Belo JC, Berndt C, et al., Sector collapse and debris avalanche escorted the 1883 Krakatau disaster, in review for Nature.

Klein E, Berndt C, Karstens J, Schindlbeck-Belo J, Preine J, Kühn M, Tappin D, Stoepeke F, Kopp H, Husrin S, Ardhyausti S, Budi Nugroho A, Karima S, Pratama A & Urlaub M, Tectonic Controls on Volcanism and edifice instability in the Sunda Strait: Insights from high-resolution Seismic Data around Krakatau, in preparation for submission to Tectonics.

List of conference presentations

2025 | **New evidence for sector collapse preceding the devastating 1883 Krakatau eruption** International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) Scientific Assembly, Geneva, Switzerland.

2025 | **The Sumatra Fault and Krakatau: How Regional Extension Shapes Volcanism in the Sunda Strait** International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) Scientific Assembly, Geneva, Switzerland.

2025 | **Marine tephrostratigraphy in the Sunda Strait (Indonesia)** International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) Scientific Assembly, Geneva, Switzerland.

2024 | **New Insights into Processes Involved in the 1883 Krakatau Eruption and Tsunami from Seismic and Hydroacoustic Data** AGU Fall Meeting, Washington, US.

2024 | **New insights to 1883 eruption of Krakatau based on high-resolution multichannel 2D seismics** International Conference on Seafloor Landforms, Processes and Evolution (ICSLPE), Lipari, Italy.

2024 | **Bio-optical characterization of surface waters underway the Indian Ocean – from Singapore to Mauritius**, Ocean Optics, Las Palmas de Gran Canaria, Spain

Data

2D multichannel seismic reflection raw data (entire dataset):
<https://doi.org/10.1594/PANGAEA.972725>

Multibeam bathymetry raw data (Kongsberg EM710 entire dataset):
<https://doi.org/10.1594/PANGAEA.968527>

Multibeam bathymetry raw data (Kongsberg EM122 entire dataset):
<https://doi.pangaea.de/10.1594/PANGAEA.968525>

Continuous optical chlorophyll-a and turbidity data:
<https://doi.org/10.1594/PANGAEA.974880>

ADCP current measurements (75 kHz):
<https://doi.org/10.1594/PANGAEA.964693>

ADCP current measurements (38 kHz):
<https://doi.org/10.1594/PANGAEA.964692>

Continuous thermosalinograph oceanography:
<https://doi.org/10.1594/PANGAEA.971727>

Cruise Report

SO299/2: https://doi.org/10.48433/cr_so299_2

SO300/1

Indian Ocean Exploration for Seafloor Massive Sulphides – INDEX2023 Leg 1 Geophysics

Authors

**Federal Institute for Geosciences and Natural Resources (BGR) | Hannover,
Germany**

U. Barckhausen, S. Bellenberg, I. Heyde, H. Müller, K. Schwalenberg

Introduction

Cruise SO300/1 (INDEX 2023) with the German RV Sonne took place in September 2023 as part of BGR's program for the exploration of polymetallic sulphides in the Indian Ocean. BGR holds a license from the International Seabed Authority which grants the exclusive right for the exploration of polymetallic sulphides in an area of 10.000 km² along the southern part of the Central Indian Ridge and the northern part of the Southeast Indian Ridge over a period of 15 years. The license area is organized in 100 blocks of 100 km² each, grouped in 12 clusters stretching out over roughly 1000 km along the two mid-ocean ridges.

Leg 1 of SO300 was dedicated to geophysical investigations and started and ended in the harbour of Port Louis, Mauritius. The cruise investigated clusters 04, 05, 06, and 09. Apart from BGR personnel, participants of cruise INDEX 2023 came from the University of Hamburg, the Integrated Environmental Solutions UG Wilhelmshaven and the Scripps Institution of Oceanography in San Diego (USA). Furthermore, two trainees with a geophysical and geological background nominated by the International Seabed Authority (ISA) from the Philippines took part. The objective of their participation was to be trained in marine exploration of seabed minerals. As observers from the coastal state of Mauritius, a geophysicist colleague from the Department for Continental Shelf, Maritime Zones Administration & Exploration of the Prime Minister's office as well as two marine biologists from the Ministry of Blue Economy, Marine Resources, Fisheries and Shipping, and the University of Mauritius participated during Leg 1. The INDEX 2023 cruise is BGR's ninth exploration campaign

in the Indian Ocean following the signing of the licence agreement with the International Seabed Authority in May 2015.

Geophysical investigations

Cruise SO300/1 took place from September 5th–28th, 2023. Due to technical problems with the ship's propulsion system and main cable winch, and rough weather, scientific work was possible during a total of 12 working days only. During this leg, electromagnetic surveys of the known JIM, SURYA, KAIMANA, and ALPHA hydrothermal fields were carried out. These are associated with occurrences of seafloor massive sulphides (SMS deposits) which are rich in metals and thus represent potential mineral resources at the seabed. The survey was realized through detailed measurements with two different devices which were deployed for measurements close to the seafloor:

1. BGR's GOLDEN EYE electromagnetic profiler operated directly at the seafloor during three long deployments for a total of 177 hours at the JIM (Cluster 09), KAIMANA (Cluster 05) and ALPHA (Cluster 04) fields.
2. The HOMESIDE/VULCAN deep towed bathymetric sled with tri-axial self-potential receivers system was used for three extensive surveys run at 50 m above the seafloor at the JIM (Cluster 09) and SURYA (Cluster 06) fields for a total operating time of 89 hours.

The goal was to map the electric and magnetic properties of the sub-seafloor at the SMS deposits and their surroundings down to a depth of a few tens of meters. In addition, the measurements provide ultra high resolution bathymetry data of the areas surveyed and many hours of video observations from the seafloor along the tracklines of the GOLDEN EYE surveys used for benthic habitat mapping.

The JIM area in Cluster 09 was surveyed for the first time with the geophysical methods and both systems were deployed over a total of eight days (including down time due to foul weather), making this the main focus of work during Leg 1. At the SURYA hydrothermal field in Cluster 06, sparse older deep-tow bathymetry measurements were augmented with a systematic survey by the HOMESIDE/VULCAN system, which, however, did not result in any indications for a larger extent of the field than was known previously. Two GOLDEN EYE surveys at the KAIMANA field in Cluster 05 and at the ALPHA field in Cluster 04 extended existing data coverage to areas with newly discovered sulphide occurrences.

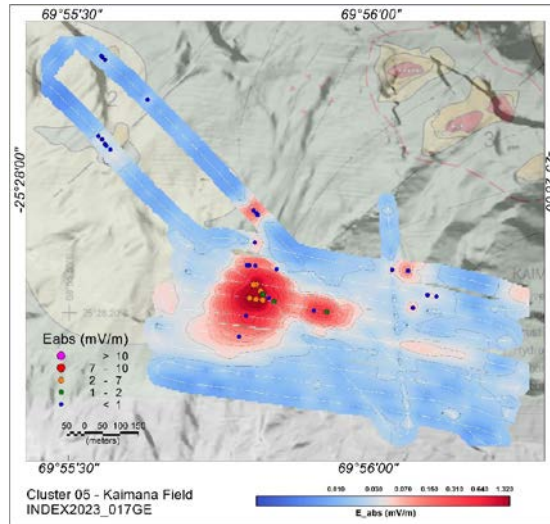


Figure 1: Self-Potential (SP) data of stations INDEX2023_017GE covering the (active) KAIMANA site: grid of absolute electric field data E_{abs} (mV/m) with manually picked and classified locations of SP anomalies and peaks.

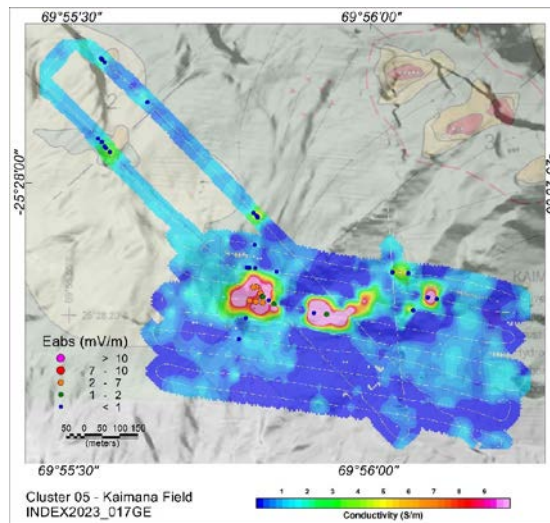


Figure 2: EM conductivity (1.6 kHz) data of stations INDEX2023_017GE covering the (active) KAIMANA site: grid of electric conductivity data (S/m) with manually picked and classified locations of SP anomalies and peaks.

Another task was the deployment of five Ocean Bottom Seismometers (OBS) at the KAIREI sulphide mound in order to record the microseismicity for a period of three months. In order to position the OBS precisely in selected spots on the inactive hydrothermal mound measuring only ~100 m in diameter, they were

lowered to the seafloor in a video-controlled frame. The OBS were recovered during cruise SO301 in December 2023.

Bathymetry, gravimetry and magnetics were measured during transits to and from the survey area and between the clusters visited, and to fill some gaps in the existing data west of clusters 06 und 05. While crossing the EEZ of Mauritius, both transits were used to map a roughly 30 km wide stripe of seafloor bathymetry with ship's EM122 multibeam system.

Scientific Output

Data

Master track:

<https://doi.org/10.1594/PANGAEA.965096>

Event list:

<https://www.pangaea.de/expeditions/events/SO300%2F1>

Thermosalinograph:

<https://doi.org/10.1594/PANGAEA.968982>

ADCP 75 kHz:

<https://doi.org/10.1594/PANGAEA.965930>

ADCP 38 kHz:

<https://doi.org/10.1594/PANGAEA.968919>

Chlorophyll & turbidity:

<https://doi.org/10.1594/PANGAEA.974884>

GE, SP, Magnetism, Gravity data:

BGR archive servers

Cruise Report

SO300: Barckhausen, U., Kuhn, and science team (2024), Cruise report SO-300 INDEX2024, Bundesanstalt für Geowissenschaften und Rohstoffe, internal report, 384 pp.

SO300/2

Indian Ocean Exploration for Seafloor Massive Sulphides

Authors

Federal Institute for Geosciences and Natural Resources (BGR) | Hannover, Germany

T. Kuhn, S. Fuchs, R. Freitag, K. Meyn

Institute for Geology, University of Hamburg | Hamburg, Germany

N. Lahajnar, N. Harms

Integrated Environmental Solutions UG | Wilhelmshaven, Germany

T. Kihara

Christian-Albrechts University Kiel, Institute for Geosciences | Kiel, Germany

D. Garbe-Schönberg

Cruise SO300/2 (INDEX 2023) with the German RV SONNE took place in October-November 2023 as part of BGR's program for the exploration of polymetallic massive sulphides in the Indian Ocean (Barckhausen & Kuhn, 2023; Figure 1). BGR holds a contract with the International Seabed Authority (ISA) which grants the exclusive right for the exploration of polymetallic sulphides in an area of 10.000 km² along the southern part of the Central Indian Ridge (CIR) and the northern part of the Southeast Indian Ridge (SEIR; Figure 1) over a period of 15 years. The contract area is organized in 100 blocks of 100 km² each, grouped in 12 clusters stretching out over roughly 1000 km along the two mid-ocean ridges. However, 75% of the contract area has to be relinquished to the ISA within the 15 years period. The exploration work comprises both geological-geophysical and environmental investigations in roughly equal proportions.

As of today, there are 16 vent fields with associated massive sulphide mineralisations known in the contract area from which 14 have been recently detected by BGR. Four of them are totally inactive and 12 contain both active and inactive sites. The number of hydrothermal sites in the individual vent fields range from 3 to 15. Some of the fields are bound to one major normal fault and then the hydrothermal sites occur like a string of pearls over distances more than 3 km in some cases. The sites within other fields are more spread out over an area up to

several square kilometers (Figure 2). Three vent fields are associated with mafic to ultramafic, plutonic rocks, whereas all other fields are hosted in basaltic rocks.

The exploration work showed that the mineralisations in the BGR contract area are often bound to sulphide mounds up to 50 m high and up to 200 m basal diameter resembling the TAG mound on the Mid-Atlantic Ridge (Hannington et al., 1998). When hydrothermally active, these mounds form steep slopes with black smoker chimneys on top. These hydrothermal mounds develop into crusted mounds and eventually become hydrothermally inactive. The crusts consist of Fe-Mn oxides and silica and seem to precipitate from low-T diffuse hydrothermal fluids at the final stage of hydrothermal activity. The crusts may preserve the hydrothermal mineralisation from oxidative weathering by seawater, at least to a certain degree and over a certain period of time (Fuchs et al., in prep.).

Massive sulphides taken from basalt-hosted hydrothermal fields in the BGR contract area are on average slightly enriched in Cu (2.2 w%), Ag (39 ppm), and Au (1.46 ppm) and ultramafic-hosted fields are strongly enriched in these elements (5.9 % Cu, 41 ppm Ag, 4.9 ppm Au) compared to average Volcanic-hosted Massive Sulphide (VMS) deposits on land (1.7% Cu, 12 ppm Ag, 0.7 ppm Au; Hannington et al., 2005; Mosier et al., 2009). In addition, ultramafic-hosted fields seem to have higher contents in some trace metals such as cobalt, selenium, and antimony.

Hydrothermal fluids could be sampled from different hydrothermal vent sites during the SO300/2 cruise using the Kiel Pumping System (KIPS) mounted to ROV ROPOS. The calculated endmember fluid compositions are similar to previous results indicating the rather stable hydrothermal activity in the investigated fields. One major finding is that the hydrothermal fluids from all hydrothermal vent fields along the Central Indian Ridge and the northernmost Southeast Indian Ridge are vapour-dominated whereas the fields located further south along the SEIR are all brine-dominated.

Environmental investigations carried out during SO300/2 included biodiversity studies of individual hydrothermal fields with active, inactive and non-vent sites, connectivity studies of vent fields along the mid-ocean ridges in the BGR contract area as well as zooplankton studies through the entire water column. Moreover, the composition and settling behavior of particles were investigated all along the BGR contract area within the framework of biogeochemical and oceanographic studies.

Biodiversity studies applied modern methods such as metabarcoding and eDNA and the results indicate minor differences in obtained numbers of operational taxonomic units of the most common taxa. The results demonstrate the potential of eDNA and metabarcoding to unravel early-stage planktonic larvae and biodiversity monitoring of vulnerable ecosystems, but requires a comprehensive

and well-validated reference library for a reliable identification. Connectivity studies of model organisms from different faunal size classes and varying dispersal capabilities included meiofauna from the subclass Acari and the copepod family Dirivultidae, macrofauna gastropods of the genus *Anatoma* and the megafauna organisms *Rimicaris kairei*, *Austinograea rodriguensis*, *Archinome jasoni*, *Bathymodiolus septemdierum*, *Alviniconcha marisindica*, and *Chrysomallon squamiferum*. All taxa showed connectivity among populations from CIR and SEIR, but low connectivity with haplotypes from the Southwest Indian Ridge (SWIR). The identified macrofauna of the genus *Anatoma* has six different species and showed a typical speciation rate with 3–5 species over a distance of 1000 km. Comparative macrofauna community studies in active, inactive and non-vent areas identified Gastropoda as the dominating group in almost all sampled areas, contradicting existing deep-sea environmental studies that indicated the presence of Gastropoda, but not as an abundant group. Zooplankton studies of sediment trap fauna identified community shifts in terms of seasonality from summer to autumn and within the middle deep fauna (i. e., about 560 m above seafloor), while shallow (about 800 m below sea surface) and deep samples (about 30 m above seafloor) were heterogenous. Copepoda was the most diverse taxon, a finding highlighted by the occurrence of eight vent-endemic species from different depth layers.

The biogeochemical and oceanographic studies show that the controlling factors of particulate organic carbon (POC) fluxes were first-order linked to surface primary production, which was in turn strongly limited by nutrients. In a global comparison, carbon fluxes in the Indian Ocean subtropical gyre were extremely low with POC fluxes of $0.5 \text{ mg m}^{-2} \text{ d}^{-1}$ on average. Enhanced regeneration of organic components and intense degradation in the upper ocean led to similar export and burial rates with only 4 % of the POC reaching the sea floor. This means that only 0.01 % of the surface primary production accumulates in surface sediments, despite a minor increase in the net primary production rates towards the southern study area. Periodic fluctuations of lower fluxes in the middle of the year (winter season) and highest fluxes at the turn of the year (summer season) correlate with the fluctuations in sea surface temperature and partly with surface wind speed. In contrast, particle fluxes anticorrelate with chlorophyll-a data. The identified water masses present in the BGR contract area, from surface to seafloor, are the Subtropical Surface Water, Subantarctic Mode Water, Antarctic Intermediate Water, Indian Deep Water and Circumpolar Deep Water, respectively. Mean current velocities range between 1.95 and 8.89 cm s^{-1} and show a strong linear correlation with depth, with highest recorded velocities at 700–800 m water depth. The first insights into the current speed and directions near the bottom potentially correlate with the general north-south topography.

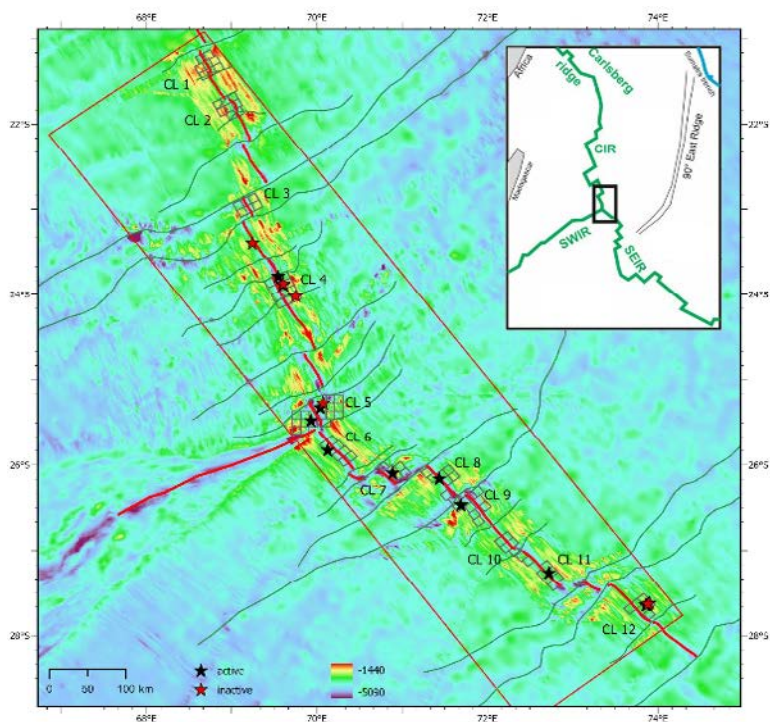


Figure 1: Size and location of the BGR contract area in the central Indian Ocean. CL1 to CL 12 mark the original exploration clusters. Active and inactive hydrothermal fields are also shown. SO300/2 worked in CL 1, 4, 5, 7-12. Background bathymetry is from GEBCO and bathymetry between CL 1 and 12 from BGR.

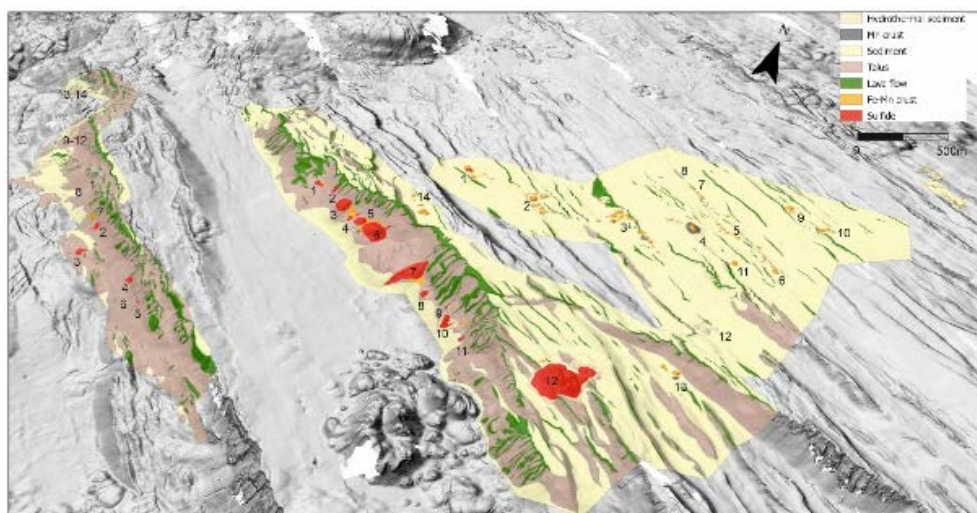


Figure 2: Perspective geological map of massive sulphide fields in Cluster 12 draped over high-resolution bathymetry. Numbers indicate individual sites in each vent field.

References

Hannington MD, de Ronde CDJ & Petersen S, Sea-floor tectonics and submarine hydrothermal systems, Society of Economic Geologists 2005, <http://eprints.uni-kiel.de/6271/>.

Hannington MD, Galley AG, Herzig PM & Petersen S, Comparison of the TAG mound and stockwork complex with Cyprus-type massive sulphide deposits, In Herzig PM, Humphris SE, Miller DJ, & Zierenberg RA (Eds), Proceedings of the Ocean Drilling Project, Scientific Results 1998, Vol. 158, 389–415.

Mosier DL, Berger VI & Singer AD, Volcanogenic massive sulphide deposits of the world: Database and grade and tonnage models, USGS Open-File Report 2009–1034, <http://mrdata.usgs.gov/metadata/ofr-2009-1034.html>.

Scientific Output

List of Publications

Dufek T, Freitag R, Kuhn T & Sternberg H, Exploration of hydrothermal venting sites using deep-towed multibeam echo sounder data, International Hydrographic Review 2024, 30/1. <https://doi.org/10.58440/ihr-30-1-c01>.

Fuchs S, Kuhn T, Meyn K, Kihara T, Freitag R, Gibson H, Bellenberg S, Klischies M, Gemmel T & Garbe-Schönberg D, The discovery of thirteen hydrothermal vent fields and associated polymetallic massive sulphides in the Central Indian Ocean, Scientific Reports, in prep.

Harms NC, Lahajnar N, Gaye B, Rixen T & Freitag R, Biogeochemistry of the South Indian Ocean - water masses, nutrient distribution, and sinking particulate matter, in: R. Sharma (editor), Deep-Sea Mining and the Water Column, Springer 2024, pp. 377-413, https://doi.org/10.1007/978-3-031-59060-3_12.

Holzheid A, Zhao H, Cabus T, Fad L, Kuhn T, Sun L, Tao C, Haeckel M, Hoang D, Kelly N, Kihara T, Li B, Li J, Mam J, Matz-Lück N, Meyn K, Molari M, Petersen S, Pollmann K, Rudolph M, Xu X & Zhang Y, Deep-sea mining of massive sulfides: Balancing impacts on biodiversity and ecosystem, technological challenges and law of the sea, Marine Policy 2024, <https://doi.org/10.1016/j.marpol.2024.106289>.

Kihara TC, Clark PF, Meyn & Klaas H, First zoeal stage of the Indian Ocean hydrothermal vent crab *Austinograea rodriguezensis* Tsuchida & Hashimoto, 2002 (Decapoda: Brachyura: Bythograeidae), Zootaxa 2024, <https://doi.org/10.11646/zootaxa.5476.1.18>.

Meyn K, Kihara TC, Sweetman AK, Martinez Arbizu P & Kuhn T, Occurrence of vent-derived organic falls and associated fauna at hydrothermal vents on the Indian Ridge: Implications for an underestimated food source at hydrothermal vent fields, Deep Sea Research Part I: Oceanographic Research Papers 2025, 104489, <https://doi.org/10.1016/j.dsr.2025.104489>.

Neufeld M, Meyn K, Kihara TC, Martinez Arbizu, P & Kuhn T, First record of the giant anemone, *Relicanthus daphneae*, at active hydrothermal vent fields in the Indian Ocean, Journal of the Marine Biological Association of the United Kingdom 2024, 104, e122, 1–6. <https://doi.org/10.1017/S0025315424001127>.

List of conference presentations

2025 | **Environmental studies in the BGR contract area**, ISA workshop on the development of a REMP for the Area of the Indian Ocean, Qingdao, China

2024 | **Diversity of demersal and seafloor scavengers along the SE Indian Ocean Ridge – initial findings from INDEX 2023 cruise**, Underwater Mining Conference, Rarotonga, Cook Islands

Data

Environmental data such as sediment geochemistry, dissolved metals in water column, biogeochemical data from sediment traps, current meter data as well as data about benthic fauna (mainly taxonomy) were uploaded to the DeepData database of the International Seabed Authority under the keyword “INDEX-2023”. Detailed specimen data and DNA sequences were uploaded in Barcode of Life Data Systems (BOLD), project «Indian Ocean Hydrothermal Vent Fauna – INDEX». These data will be accessible for the scientific community after a certain moratorium period.

Cruise Report

SO300/2: Barckhausen, U. & Kuhn, T. (Eds.), Indian Ocean Exploration for Seafloor Massive Sulphides – Cruise Report INDEX 2023. Federal Institute for Geosciences and Natural Resources (BGR), 2024, Hannover, Germany, 383 pp.

SO301

Seismic Imaging at the Central Indian Ridge: Structure and Formation of Oceanic Core Complexes (SCIROCCO)

Authors

Federal Institute for Geosciences and Natural Resources (BGR) | Hannover, Germany

M. Engels, M. Schnabel, H.-S. Hilbert, T. Fridrich, B. Schramm, U. Barckhausen, I. Heyde, S. Ladage

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

A. Dannowski, O. Luecke, A. Jegen, L. Bitzan, I. Grevemeyer

MARUM - Center for Marine Environmental Sciences, University of Bremen | Bremen, Germany

G. Wegener, J. Mette, M. Walter, W. Bach

Constructor University | Bremen, Germany

N. Fröhberg, I. Pedre, A. Koschinsky

Max Planck Institute for Marine Microbiology | Bremen, Germany

L. Gallucci, A. Meyerdierks

Introduction

Cruise SO301 investigated an Oceanic Core Complex (OCC) at 25°S, 70°E, the Kairei hydrothermal vent field at the Central Indian Ridge north of the Rodriguez Triple Junction as well as the three corresponding plate boundaries. The geophysical project SCIROCCO acquired 29 reflection seismic profiles using an 8 km long streamer (BGR part) and refraction data from 85 ocean bottom seismometer (OBS) sites (GEOMAR part). The secondary project KABA studied the Kairei plume through oceanographic, biogeochemical and microbiological sampling.

Reflection seismics (BGR)

To analyse i) the OCC, ii) the conjugate crusts of the Somali, Indo-Australian and Antarctica plates, and iii) the Kairei hydrothermal field, we applied multichannel seismics (MCS) and streamer tomography. The long streamer enabled picking refracted phases after downward continuation of the wave fields. 2D tomography provided a high-resolution upper crust velocity structure.

The OCC contains four domains distinguished by reflection patterns and velocity structure (Figure 1c, d). We detected rafted blocks from the hanging wall, high velocity mantle rock anomalies, a shallow reflector indicating a mylonitic shear zone, and derived an evolution model using magnetics for age estimation.

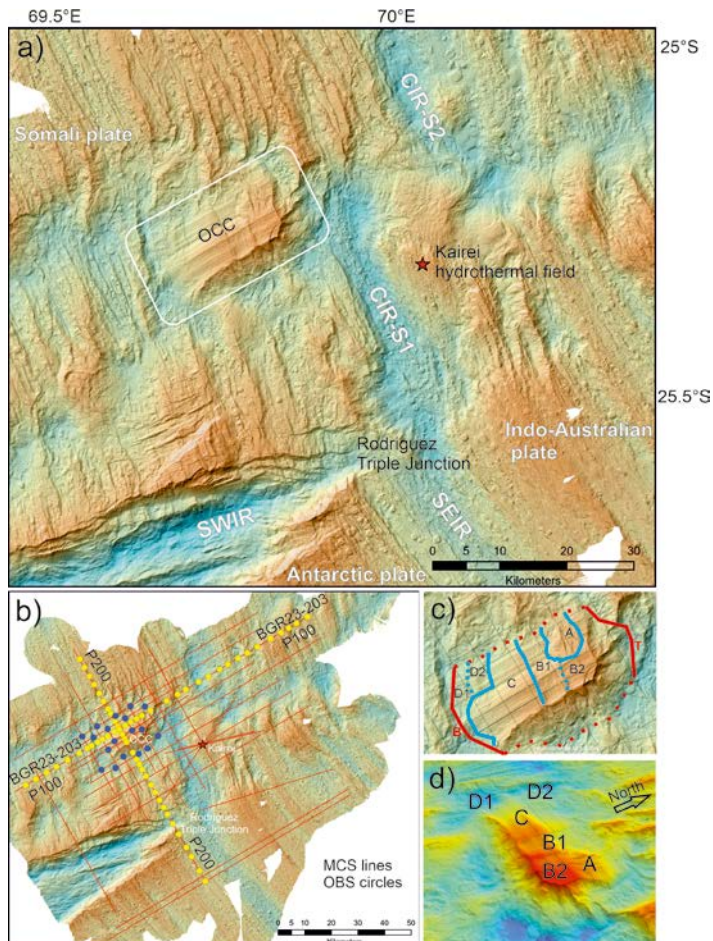


Figure 1: **(a)** Bathymetry of SO301 survey area, **(b)** MCS profiles (red lines) & OBS stations along 2 refraction profiles P100 (BGR23-203) & P200 (yellow circles) and around the OCC (blue circles), **(c)** OCC domains, A & D with rafted blocks, **(d)** OCC in a perspective view from above the ridge axis towards west.

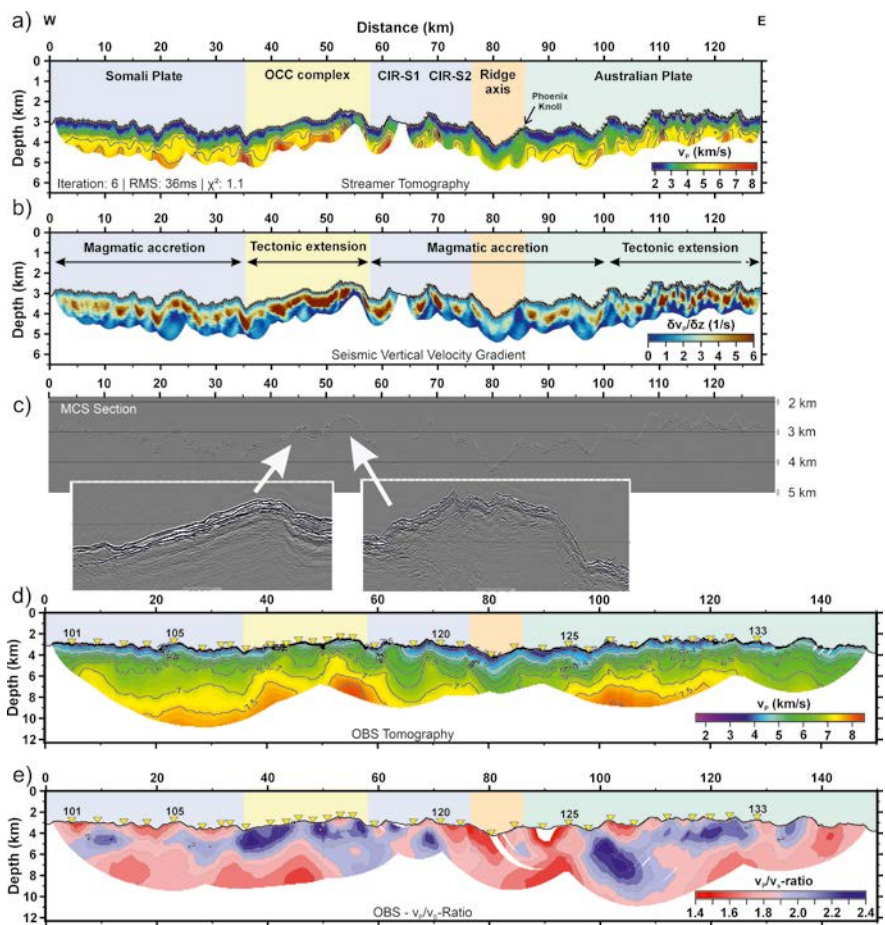


Figure 2: Line BGR23-203 (P100; Figure 1b): (a) streamer tomography: v_p -velocities, (b) vertical velocity gradients and labelled tectonic regimes, (c) MCS section after pre-stack depth migration with enlargements of OCC domains C (left) & A (right), (d) OBS tomography: v_p -velocities, (e) OBS v_p/v_s ratio confirming tectonic regimes.

The conjugated crusts can be divided in distinct zones by velocity gradients and reflection patterns: Tectonic extension regimes occur even beyond the OCC with high velocities indicating incorporated deep rocks in the upper crust, while other zones show typical magmatic accretion behaviour.

The Kairei hydrothermal field was investigated by MCS, streamer tomography and 3D tomography using OBS data. Shallow high velocities, ~500 m below Kairei, indicate deep rocks causing serpentinization driven by H_2 -rich hydrothermal fluids, possibly fed by inflow from the central valley.

Refraction seismics (GEOMAR)

To study the deep structure of the OCC, its conjugated ridge flanks, and its north-south extent, two wide-angle refraction seismic profiles were acquired. Profile P100 runs in SE-NW direction across the OCC, and thus follows the direction of spreading. East of the OCC, the profile continues covering a doomed ridge axis of the CIR-1 segment and the currently active ridge axis of the CIR-2 segment. The NE-SW profile P200 also provides information on the deeper velocity structure and crustal thickness of two distinct domains of seafloor bounding the core complex to the south and north, as well as on the easternmost SWIR segment and the Antarctic Plate. Along both profiles, converted S-phases were identified, allowing the derivation of v_p/v_s models (i. e. Figure 2e). A total of 35 OBS were deployed on and in the vicinity of the OCC to enable 3D travel time tomography. The seismic interpretation is supported by 3D gravity modelling.

Beneath the OCC, high P-wave velocities were observed, consistent with gabbroic and ultramafic rocks. The OCC flanks, by contrast, exhibit lower velocities, indicating faulting and serpentinization in the shallow subsurface, as well as possible scree deposits on the southern end. Elevated crustal seismic velocities south of the OCC may reflect smaller mafic and ultramafic massifs.

Crustal accretion on the Somali Plate, both south and north of the OCC, appears to be dominated by magmatic processes. In contrast, the Australian plate shows elevated v_p/v_s ratios in the upper 2 km of the subsurface, pointing to tectonic processes playing a stronger role in accommodating seafloor spreading. The ultraslow-spreading SWIR axis is characterised by high mantle velocities and an asymmetric ridge valley. Toward the southeast, the Antarctic Plate exhibits a typical layered structure with well-defined crust and velocities reaching 7.1 km/s at crust-mantle boundary.

The SCIROCCO project complemented by a passive seismic experiment. Results show a shift of seismicity away from the central valleys, northwards along the SWIR and eastwards along the CIR. This indicates a steady relocation of the axial valleys and the corresponding meeting point of the three ridges progressively toward the northeast.

Kairei hydrothermal plume (KABA project)

The SO301 expedition's KaBa project surveyed the hydrothermal plume from the Kairei Hydrothermal Field (KHF) to study biogeochemical cycling in the bathypelagic ocean. Plume size and distribution were mapped with CTD tow-yo surveys using turbidity and electrochemical sensors. Water samples, collected with a trace-metal-clean rosette and ship's CTD, were analyzed for dissolved

metals, gases (H_2 , CH_4), and organic carbon. Microbial communities were examined using sequencing and molecular techniques.

Results: Turbidity profiles revealed plume dispersal within the water column (**Figure 3a**). Water samples showed strong enrichment of manganese, cobalt, and iron, while copper and nickel increased with depth but not in the plume. Cadmium depletion suggested co-precipitation (**Figure 3b**). Microbial analysis (**Figure 4**) indicated the enrichment of *Sulfurovum* in the rising plume, likely dispersed via buoyancy, and *Sulfurimonas* dominance in the non-buoyant plume, consistent with hydrogen oxidation by *Ca*. *Sulfurimonas pluma* (Molari et al., 2023). SUP05 bacteria were moderately enriched. Methane appeared only near the rising plume, while hydrogen declined faster than dilution predicted, supporting microbial oxidation. These results clarify plume dispersion, trace metal cycling, and microbial use of reduced compounds within the hydrothermal plumes of KHF.

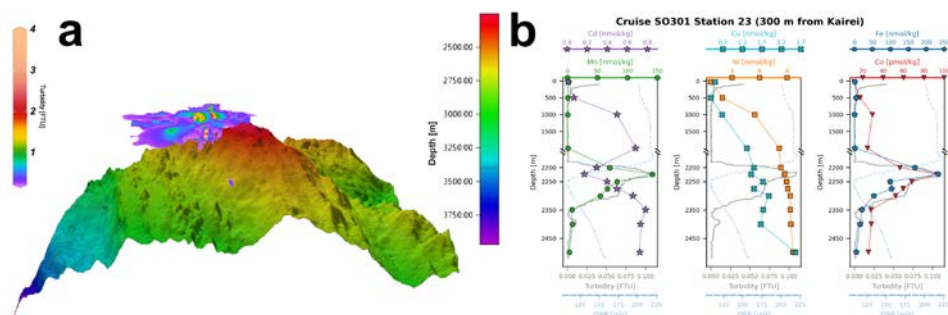
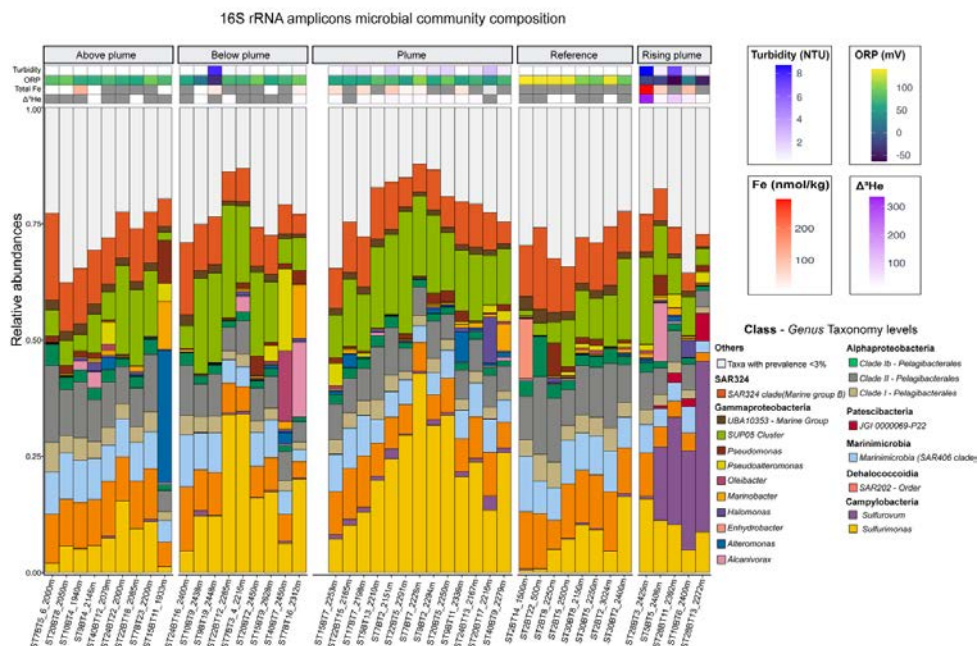


Figure 3: **Contour map and trace metal profiles from the Kairei vent field.** a) Bathymetric map of the Kairei vent area showing the hydrothermal plume extending to ~100 m above the vent site. b) Selected profiles of dissolved trace metals from Station 26. Figure prepared by Nico Fröhberg, Constructor University and modified by Gunter Wegener, MARUM.



Dannowski A, Grevemeyer I, Engels M, Schramm B, Jegen A, Luecke O, Barckhausen U, Ladage S & Heyde I, P- and S-wave crustal structure of the 25°S OCC and a NTO north of the Rodriguez Triple Junction, in preparation for JGR.

Dannowski A, Bitzan L, Grevemeyer I, Engels M & Schnabel M, Three-dimensional structure of the Oceanic Core Complex at 25°S, in preparation for JGR.

Fröhberg N, Pedre I & Koschinsky A, From Source to Sink: Complex Dual Role of the Kairei Hydrothermal Plume in Deep Ocean Trace Metal Cycling at the Central Indian Ridge, in preparation.

Hilbert H-S, Engels M, Schnabel M, Fridrich T, Schramm B, et al., Integrated MCS and Streamer Tomography Imaging of the 25°S Oceanic Core Complex at the Central Indian Ridge, in preparation for GJI.

Luecke OH, Dannowski A, Engels M, Grevemeyer I, Heyde I, et al., Seismic Velocity Structure and Tectonic Segmentation of the Southwestern Somali Plate at the Rodrigues Triple Junction, in preparation for GJI.

List of conference presentations

2024 | **P- and S-wave seismic velocity structure of the 25 °S OCC north of the Rodriguez Triple Junction at the Central Indian Ridge extracted from ocean bottom seismometer of Talk**, DGG, Jena, Germany.

2024 | **Seismic velocity structure of the 25 °S OCC north of the Rodriguez Triple Junction at the Central Indian Ridge extracted from ocean bottom seismometer**, EGU, Vienna, Austria.

2024 | **The internal structure of an Oceanic Core Complex at the Central Indian Ridge as deduced from streamer tomography**, SEISMIX, Uppsala, Sweden.

2024 | **Seismic imaging of the Central Indian Ridge focusing on the 25° S Oceanic Core Complex and the Kairei hydrothermal field**, AGU, Washington, USA.

2024 | **Seismic Velocity Structure and Segmentation of the 25°S Oceanic Core Complex and along the Central and Southwest Indian Ridges near the Rodriguez Triple Junction**, AGU, Washington, USA.

2024 | **Exploring the Complex Dynamics of the Rodriguez Triple Junction: Insights from New Seismological Data**, AGU, Washington, USA.

2024 | Microbiology and geochemistry of the deep-sea Kairei plume: 16S rRNA taxonomy and functional prediction of microbial communities D-A-CH 3rd Geobiology Symposium 2024, Bayreuth, Germany

2025 | Seismic structure of the 25 °S OCC north of the Rodriguez Triple Junction at the Central Indian Ridge, International Earthquake Science Symposium, Yokosuka, Japan.

2025 | Meta-omics mining of active microbial communities in hydrogen and iron-rich deep-sea hydrothermal plumes Goldschmidt 2025, Prag, Czechia.

2025 | 3D Seismic Tomography in Combination with Geophysical Imaging of the Kairei Hydrothermal Field – a Study of the Fluid Flow System at the Central Indian Ridge, AGU Fall Meeting 2025, New Orleans, USA.

2025 | Structure and Evolution of the 25° S Oceanic Core Complex at the Central Indian Ridge based on Traveltime Tomography using downward continued 2D Streamer data, AGU Fall Meeting 2025, New Orleans, USA.

Data

MCS reflection data:

<https://doi.pangaea.de/10.1594/PANGAEA.984451>

Multibeam bathymetry EM122:

<https://doi.pangaea.de/10.1594/PANGAEA.984415>

Multibeam water column EM122:

<https://doi.pangaea.de/10.1594/PANGAEA.984416>

Thermosalinograph:

<https://doi.pangaea.de/10.1594/PANGAEA.971728>

ADCP 75 kHz:

<https://doi.org/10.1594/PANGAEA.971509>

ADCP 38 kHz:

<https://doi.org/10.1594/PANGAEA.971508>

Chlorophyll & turbidity:

<https://doi.org/10.1594/PANGAEA.974969>

Master track (1s resolution):

<https://doi.org/10.1594/PANGAEA.967549>

MCS, Magnetics, Gravity data:

BGR archive servers

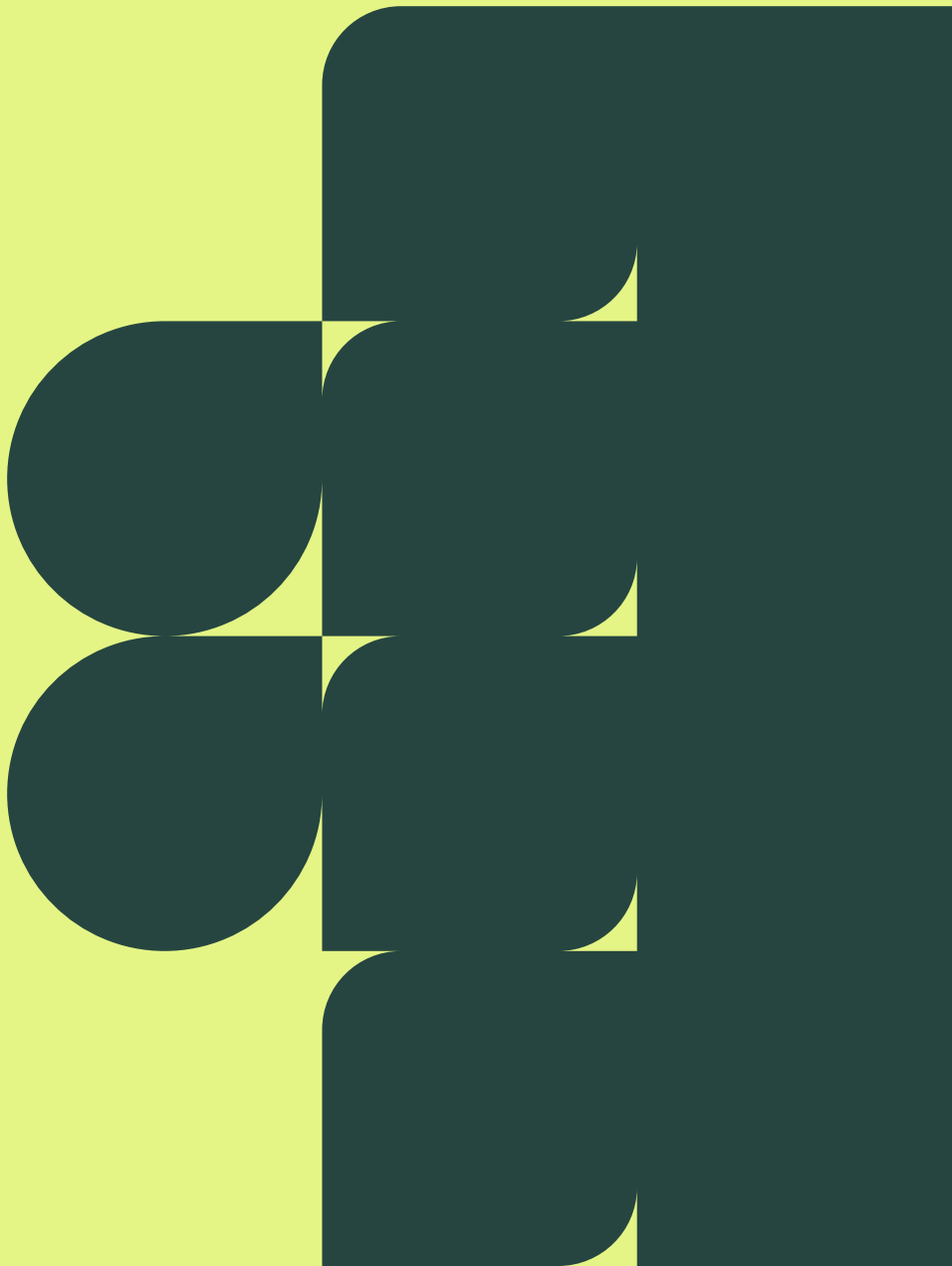
OBS data:

GEOMAR archive servers

Cruise Report

SO301: https://doi.org/10.48433/cr_so301

Poster



HE598, HE609, HE61 and HE626

Bridging Surface and Subsurface Salinity Measurements Using Machine Learning

Authors

Institute of Chemistry and Biology of the Marine Environment, Centre of Marine Sensors (ZfMarS), University of Oldenburg | Wilhelmshaven, Germany

S. M. Ayim, L. Jaeger, L. Gassen-Bertzbach, O. Wurl

This study investigates the relationship between sea surface salinity (SSS) in the skin layer of the ocean and sub-surface salinity measurements. The skin layer is less than 1 mm thick, has unique physical, chemical and biological properties and it corresponds to the penetration depth of satellite measurement. The sub-surface salinity measurement was taken at approximately two meters depth (near-surface layer, NSL) by the thermosalinograph (TSG) onboard the research vessel RV Heincke. The high-resolution per-second skin salinity dataset utilized in this research is from the autonomous surface vehicle HALOBATES. Additionally, HALOBATES provides concurrent measurement from one-meter depth and data of essential climate variables such as air temperature, wind speed and direction. The data collection spanned four research cruises, collectively referred to as SCANS, conducted in the North Sea in 2022 and 2023, providing over 170 hours of continuous salinity and environmental observations. The datasets are from the cruises HE598 (May 2022), HE609 (October 2022), HE614 (March 2023), HE626 (July/August 2023). By integrating these datasets, we quantify the vertical salinity gradient and develop a predictive tool capable of inferring sub-surface salinity dynamics from skin layer observations.

Our approach involved several stages, including data acquisition, cleaning, and pre-processing. In-situ measurements from HALOBATES were extracted, capturing key variables including skin layer salinity, NSL salinity, water temperature at both the skin layer and 1 m depth, air temperature, and wind speed. These datasets

were harmonized with the TSG's data and only data from the minute mark are used. Following data alignment, feature engineering was performed to enhance the predictive power of the model. Temporal features such as the day of the year, hour, and minute were transformed into decimal time representations to capture diurnal variations. The spatial coordinates of latitude and longitude were retained to account for spatial heterogeneity in salinity patterns. The final predictor set for modelling included skin and NSL salinity and temperatures, air temperature, wind speed, temporal descriptors, and geographic location. The target variable was the TSG's NSL salinity (SSS at ~2 m depth), providing a link between the skin layer and the sub-surface water measurements.

A feed-forward neural network was constructed to model the relationship between the skin layer observations and NSL salinity from the TSG. The neural network architecture comprises an input layer corresponding to the ten selected predictor variables, followed by two fully connected dense layers with 128 and 64 neurons respectively, utilizing Rectified Linear Unit (ReLU) activation functions. A dropout layer with a rate of 0.2 was incorporated to mitigate overfitting, and the output layer consists of a single neuron to predict the NSL salinity. The model was trained using the Adam optimizer with mean squared error (MSE) as the loss function and mean absolute error (MAE) as an additional metric. Training employed an 80/20 train-test split and included a validation split of 20% within the training data. Standard scaling was applied to all predictor variables to normalize the input features, ensuring balanced contributions to the model's learning process.

Once trained, the model demonstrated substantial predictive skill, capturing the relationship between skin layer measurements and NSL salinity with a root mean squared error (RMSE) of 0.384, mean absolute error (MAE) of 0.297, and a coefficient of determination (R^2) of 0.769. These performance metrics indicate that the neural network successfully learns the underlying patterns in the data, providing a reliable tool for estimating sub-surface salinity based on skin layer observations. Residual analysis further confirmed the model's robustness, with residuals evenly distributed around zero and no significant heteroscedasticity observed across predicted and actual salinity ranges. In addition to predictive accuracy, the model's interpretability was addressed through permutation-based feature importance analysis. Results revealed geolocation and the season are relevant in deducing the NSL salinity.

By demonstrating that sub-surface salinity can be accurately inferred from skin layer measurements combined with auxiliary variables, the neural network provides a practical tool for bridging the vertical gap between the sea surface and slightly deeper layers. This has potential applications for coastal monitoring, remote sensing calibration, and the integration of autonomous surface vehicles into operational observing systems. Moreover, the approach supports the broader use of satellite-derived SSS data by providing a means to reconcile satellite skin

layer measurements with in-situ sub-surface observations, thereby enhancing the utility of satellite products for regional oceanographic studies. Future directions include refining the neural network architecture, exploring recurrent or convolutional neural network structures to better capture temporal dependencies and spatial patterns. Additional environmental covariates such as solar radiation and precipitation could be integrated to further improve model performance. The extended dataset and model outputs will also allow for detailed analysis of vertical salinity gradients under different meteorological and hydrodynamic conditions, contributing to improved understanding of coastal mixing processes and salinity-driven biogeochemical dynamics.

M190

Geochemistry of fluids from hydrothermal systems at the Mid-Atlantic Ridge 29–38°N

Authors

Constructor University Bremen | Bremen, Germany

E. Meckel, L. Klose, A. Koschinsky

University of Bremen and MARUM – Center for Marine Environmental Sciences | Bremen, Germany

S. Bhaumik, S. Kasemann, W. Bach, A. Diehl

University of Münster | Münster, Germany

H. Strauss

During expedition M190, we investigated the discharge of dissolved metals from hydrothermal systems and their distribution along the rising and non-buoyant plume above the Mid-Atlantic-Ridge (MAR) between 29°10'N and 37°50'N. In greater detail we wanted to understand the variability of those fluids between km-separated vents and if we can distinguish different controls on this variability such as host-rock geochemistry, volcanism and faulting. Furthermore, the transformation or complexation of dissolved metals within the rising and non-buoyant plume has been of major interest, with a focus on understanding the fate of metals and how it is affected by metal/sulfide and metal/carbon ratios. Besides understanding the diversity of these systems, our dedicated sampling strategy of probing the emerging fluids at the seafloor, as well as the rising and non-buoyant plumes will provide insights into microbial processes within the water column and the cycling of hydrothermally derived metals in the Atlantic Ocean.

Geological background

Hydrothermal systems along the MAR are key to understanding fluid-rock interactions, geochemical cycling, and biological activity at slow-spreading

oceanic plate boundaries. Unlike fast-spreading ridges, the MAR is characterized by lower magmatic heat flux and pronounced tectonic segmentation, leading to more spatially heterogeneous hydrothermal structures. Overall, hydrothermal systems along the MAR – including Rainbow, TAG, and Lost City – highlight the diversity of geological settings and biogeochemical processes at slow-spreading ridges. They provide crucial insights into seafloor mineralization and extremophile ecosystems.

A particularly noteworthy example is the Rainbow Hydrothermal System, located at 36°13.8'N–33°54.15'W. The Rainbow hydrothermal vent site is situated on a massif composed predominantly of serpentinitized peridotites. This ultramafic host-rock acts as a source for distinct geochemical signatures of the vent fluids. Rainbow emits high-temperature (>365 °C), low-pH fluids that are rich in iron, hydrogen, methane, and other reduced species (Koschinsky et al., 2020, Seyfried et al., 2011). These chemical profiles result from extensive serpentinization reactions, which facilitate the abiotic synthesis of hydrocarbons – processes of high relevance to studies on the origin of life and deep carbon cycling (McCollom et al., 2007).

Methods

The four study sites of cruise M190 were the Broken Spur Hydrothermal Field, diffuse outflows at the Main Lucky Strike Hydrothermal Field, the Rainbow Hydrothermal Field (including the Rainbow pits) and the Menez Gwen Hydrothermal Field, where we sampled high temperature hydrothermal vent fluids with temperatures exceeding 300°C and diffuse outflows with temperatures between 20°C and 200°C. Selected seafloor images of the sampled sites are shown in Figure 1.

Fluid samples were taken with KIPS (Kiel Pumping System, Garbe-Schönberg et al., 2006) via a titanium tube attached to MARUM QUEST's ROV (Remotely Operated Vehicle) or with Ti-syringe samplers (Major samplers). KIPS samples were pumped through coiled PFA tubing and collecting in 750 ml Teflon flasks and Ti-syringes (750 ml) were directly filled via suction over a mechanical spring triggered via the ROV's manipulator. After recovery, samples were immediately filtered (0.2 and 0.8µm PES filter) and acidified to pH 2 for further analyses. Eh, pH, Conductivity and H₂S were measured immediately on board.

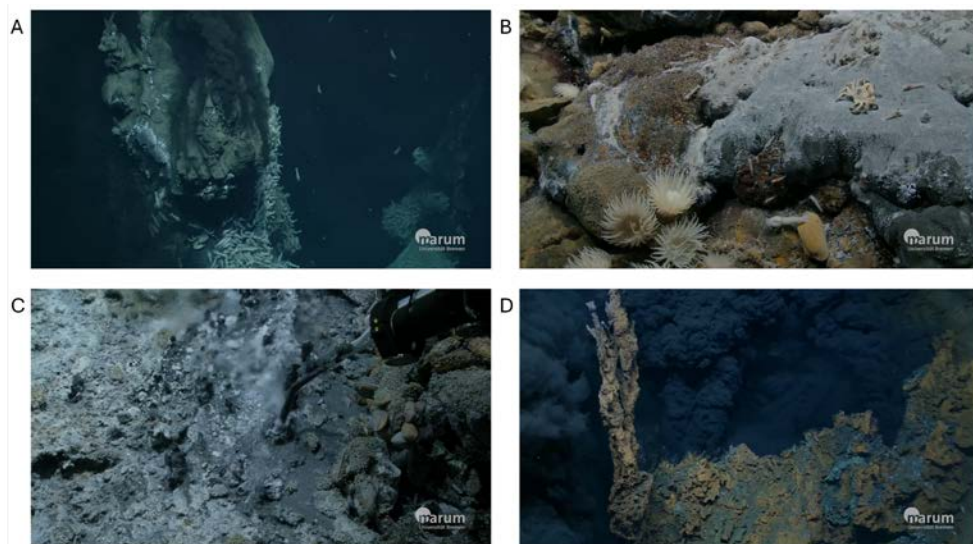


Figure 1: Selected photos of sampled vent sites A: Black smoker chimneys at the Broken Spur hydrothermal vent field at a depth of 3000 m. The black smoke is generated by precipitation of iron sulfides (FeS) due to rapid cooling. B: Vent fauna (anemones, mussels, crabs and shrimps) close to the venting areas of the Broken Spur hydrothermal vent field. C: Chimney structures at the Rainbow hydrothermal vent field. D: Sampling of a diffuse outflow with the KIPS. Source: ROV MARUM Quest 4000.

Geochemistry of vent fluids

The pH of all sampled fluids showed slightly acidic values with elevated H_2S concentrations at all sites (Table 1). Yet, the vent fields differed in their chlorinity highlighting phase-separation below the seafloor prior to venting. Broken Spur and Menez Gwen showed lower chlorinities than seawater. These chlorinities suggest the formation of a vapor-phase or a chlorine poor fluid in the subsurface at these sites. Rainbow vent fluids, on the other hand, showed higher chlorinities than seawater suggesting the occurrence of a brine-phase in the subsurface. As already shown in other studies, our geochemical analyses confirmed phase-separated fluid discharge at all four investigated sites (Douville et al., 2002). Furthermore, volcanic-hosted vent systems can show a very large diversity in fluid composition, as consequence of different magmatic stages and intensities of water-rock interactions. The fluids sampled at Rainbow hydrothermal vent field show high metal concentrations compared to the other sampled vent sites (Broken Spur, Menez Gwen and Bubblylon at Lucky Strike), especially for Fe, Mn, Ca, B, Sr, Si and other metals shown in Table 1. Recent publications suggest these properties can be explained by multiple stages of phase separation, where high chlorinity fluids originate as the conjugate low-salinity fluid of highly saline residual brines (Evans et al., 2024). In contrast to the high metal load, Rainbow fluids show lower H_2S concentrations than fluids from Broken Spur and Menez Gwen. Where else Broken Spur and Menez Gwen have low metal concentrations compared to Rainbow.

Apart from the metal concentrations, we investigated the isotopic signatures for lithium (Li), boron (B) and strontium (Sr). The findings depict notable differences in isotopic compositions, reflecting variations in the geological environments. Li concentrations in all end-member hydrothermal vent fluids are higher than in seawater, resulting from leaching of Li from the oceanic crust at high temperatures. $\delta^7\text{Li}$ values are around 5‰ at Rainbow, Broken Spur, and Menez Gwen indicating significant water–rock interaction between seawater and MORB (Mid-oceanic ridge basalt). Sr is enriched in case of Rainbow, Menez Gwen, but depleted in Broken Spur. Sr is leached at high temperature leading to its enrichment in the vent fluids, while the vent fluids from Broken Spur interact with weathered crust, which could be an explanation for depletion in those fluids. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios range from 0.7039 to 0.7050, which is less radiogenic than seawater and indicate a rock-dominated fluid–rock interaction. B enrichment varies across all vent sites. The vent fluids from Broken Spur and Menez Gwen are enriched in B, due to leaching of B from the host rocks at elevated temperatures whereas the vent fluids from Rainbow are depleted in B, due to the preferential uptake of B, by the alteration phases like serpentine. $\delta^{11}\text{B}$ values range from 15‰ to 23‰ for Rainbow, Broken Spur, and Menez Gwen, which is lower than seawater, due to the low initial $\delta^{11}\text{B}$ of the interacting oceanic crust.

		Diffuse outflow						
		Broken Spur	Rainbow	Rainbow Pits	(near Lucky Strike)	Bubblon	Menez Gwen	Seawater
$T_{\max}$	[°C]	368	360	95	24	278	295	-
pH		4.9	3.1	6.2	6.3	5.1	4.4	-
H_2S	[$\mu\text{m/L}$]	3091	1449	552	278	1385	3552	-
Cl-	[mmol/kg]	427	647	486	508	444	329	473
Br-	[$\mu\text{mol/kg}$]	701	1011	789	826	717	528	749
SO_4^{2-}	[mmol/kg]	11.4	1.4	14.8	26.0	20.2	4.4	25.2
Si	[mmol/kg]	9.9	8.0	2.2	1.0	2.5	9.7	<LOQ
Na	[mmol/kg]	448	570	424	464	434	294	459
K	[mmol/kg]	13.8	19.7	11.5	10.9	11.2	17.8	10.1
Ca	[mmol/kg]	11	69	15	11	13	23	10
Li	[mmol/kg]	0.49	0.34	0.13	<LOQ	<LOQ	0.20	<LOQ
Sr	[mmol/kg]	<LOQ	0.20	0.08	0.09	0.08	0.10	0.07
Mn	[mmol/kg]	0.19	1.75	0.17	0.01	0.02	0.08	<LOQ
Fe	[mmol/kg]	0.43	18.9	0.03	0.02	0.03	<LOQ	<LOQ
B	[mmol/kg]	0.46	0.33	0.37	0.45	0.43	0.41	0.41
Mg	[mmol/kg]	25.61	2.38	42.50	51.48	41.88	8.66	50.45

Table 1: Overview of measured geochemical data for the different venting sites. Within 0–5 % difference to IAPSO: Ca, Fe, K, Mn, Na, S. Within 5–10% difference to IAPSO: Li, Mg, Sr, Si

We collected first fluid samples of the Rainbow Pits, which revealed diffuse venting with temperatures up to 95 °C, associated with slightly reduced chlorinity compared to seawater and high H₂S concentrations. These areas were covered with mussels and other biota, implying a favourable energetic landscape provided by these diffuse vent sites. To further understand the relation between the Rainbow Pits and the Main Rainbow vent site and to discover more diffuse and focused venting sites along the MAR a follow-up cruise M210 was conducted in April/ May 2025.

Outlook

We aim to further characterize the molecular composition of dissolved organic matter (DOM) in the fluids, as well as rising and non-buoyant plumes. Aliquots for DOM analyses were taken, acidified and solid-phase-extracted for measurements at a FT-ICR-MS (Fourier Transform – Ion Cyclotron Resonance – Mass Spectrometer). We will measure metal-organic complexes at the FT-ICR-MS to understand the role of metal-DOM interactions during the transport of hydrothermally derived metals into the water column. In addition, we will use the isotopic signatures of Li, Sr and B, to identify the parameters which influence the partitioning of metals between precipitated and dissolved matter from different hydrothermal sources.

Acknowledgments

We would like to thank Annika Moje, Patrick Monien and Jenny Wendt as part of the sampling team, as well as the whole team on-board the R/V Meteor. We would like to acknowledge the Deutsche Forschungsgemeinschaft (DFG) for funding Research expedition M190 under grant – EXC-2077-The Ocean Floor Earth's Uncharted Interface – 390741603.

References

Douville E, Charlou JL, Oelkers EH, Bienvenu P, Jove Colon CF, Donval JP, Fouquet Y, Prieur D, Appriou P, The rainbow vent fluids (36°14'N, MAR): the influence of ultramafic rocks and phase separation on trace metal content in Mid-Atlantic Ridge hydrothermal fluids, *Chemical Geology* 2002, 184(1-2), 37-48, [https://doi.org/10.1016/S0009-2541\(01\)00351-5](https://doi.org/10.1016/S0009-2541(01)00351-5).

Evans G, Awolayo AN, Tutolo BM, Seyfried WE, Geochemical constraints on reaction temperature and pressure and heat- and mass-transfer efficiency at Rainbow Hydrothermal Field, *Earth and Planetary Science Letters* 2024, 648, <https://doi.org/10.1016/j.epsl.2024.119063>.

Garbe-Schönberg D, Koschinsky A, Ratmeyer V, Jähmlich H, Westernstroeer U, KIPS – a new multiport valve-based all-Teflon fluid sampling system for ROVs, *Geophys* 2006.

Koschinsky A, Schmidt K, Garbe-Schönberg D, Geochemical time series of hydrothermal fluids from the slow-spreading Mid-Atlantic Ridge: Implications of medium-term stability, *Chem. Geol.* 2020, 552, 119760.

McCollom TM, Seewald JS, Abiotic Synthesis of Organic Compounds in Deep-Sea Hydrothermal Environments, *Chem. Rev* 2007, 107, 382–401.

Seyfried WE, Pester NJ, Ding K, Rough M, Vent fluid chemistry of the Rainbow hydrothermal system (36°N, MAR): Phase equilibria and in situ pH controls on seafloor alteration processes, *Geochim. Cosmochim. Acta* 2011, 75, 1574–1593.

M194

Discovery of high-temperature hydrothermalism and massive sulfide formation at Hatiba Mons volcano, Central Red Sea

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

I. Diercks, S. Petersen, J. Follmann, S. G. Sander (+Kiel University)

OceanQuest, KAUST | Thuwal, Kingdom of Saudi Arabia

N. Augustin

King Abdullah University of Science and Technology (KAUST) | Thuwal, Kingdom of Saudi Arabia

F. M. van der Zwan

Kiel University | Kiel, Germany

S. G. Sander

A series of expeditions conducted by a multitude of research vessels (RV Albatross, RV Atlantis, RV Atlantis II, RV Meteor, RV Discovery, RV Chain) in the late 1940s and then during the early 1960s lead to the discovery of hot brines and hydrothermal metal deposits in the Discovery and Atlantis II Deeps (Bruneau 1953; Miller et al., 1966) in the Central Red Sea (Degens and Ross, 1969). These findings in turn stimulated active interest in submarine hydrothermal systems, reinforcing the view that conductive heat flow alone was insufficient to account for the Earth's excess heat loss, which instead required advective discharge through circulating seawater. Since the discovery of deep-sea hydrothermal vent systems at the Galápagos Rift in 1977 (Corliss et al., 1979), these environments have been recognized as unique ecosystems that support chemoautotrophic communities and play a crucial role in global geochemical cycles and mineral deposit formation.

Despite several decades of research, the first active hydrothermal systems were not observed in the Red Sea until 2022 (van der Zwan et al., 2023). Following up with a cruise on RV Meteor in 2023 (M194, Augustin et al., 2024), we conducted a detailed investigation of these systems, with ROV observations and intensive sampling of surface crusts, microbial mats, brines, vent fluids as well as sediment, rock and pore-fluid sampling using gravity corers with a particular focus on newly identified sites at Hatiba Mons volcano.

Hatiba Mons is the largest axial dome-shaped volcano in the ultra-slow spreading Red Sea rift, with a basal diameter of 11.4 km and a height of 530 m above the seafloor (Augustin et al., 2016). Indications of recent magmatic activity (<1,000 yrs), a low crustal magnetization at the summit, and high chlorine values in the surrounding basalts, suggested Hatiba as a prime location for the presence of hydrothermal activity (van der Zwan et al., 2015; Augustin et al., 2016; van der Zwan et al., 2023). Moreover, hydrothermal systems at ultra-slow spreading ridges represent prospective locations to host large metal deposits (Hannington et al., 2011; German et al., 2016). Hatiba Mons is unique not only within its regional context, as the largest submarine magmatic centre in the Red Sea, but also compared to other large axial volcanoes globally. It hosts widespread hydrothermal activity, estimated to cover a total area of about 1.6 km², which exceeds the dimensions of all other known active sites globally, and is characterized by remarkably extensive iron deposits in the form of iron mounds (Fe-mounds) (van der Zwan et al., 2023). These systems provide a unique opportunity to examine the interactions between geochemistry and microbial life in metal-rich environments. Upon the discovery in 2022, in light of the measured in situ temperatures of around 40°C, the observation of abundant brittle Fe-crusts and the absence of any sulfides and other high-temperature mineral phases such as anhydrite, suggested that only low-temperature venting is presently occurring at the Hatiba vent fields (van der Zwan et al., 2023).

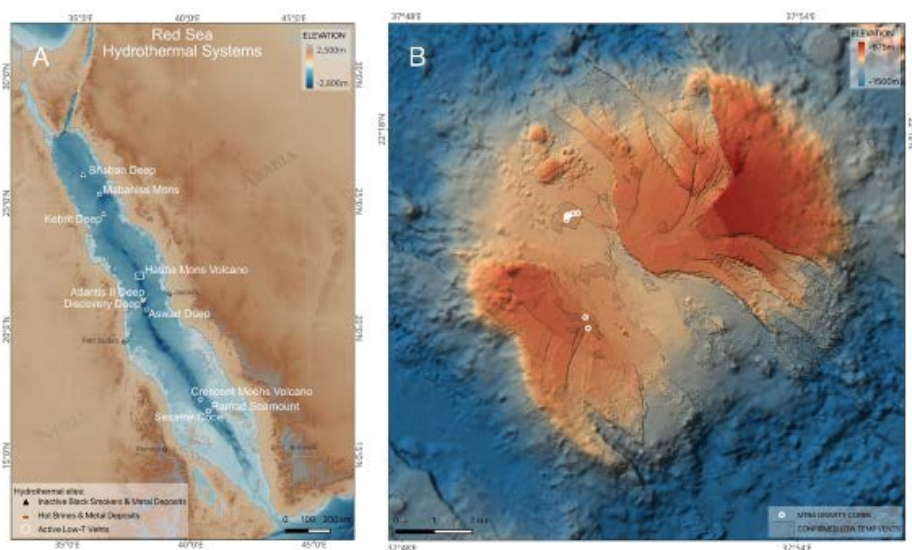


Figure 1: A) Overview of the Red Sea with recently discovered active hydrothermal systems (van der Zwan et al, 2023; M194, Augustin et al., 2024), inactive massive sulfide deposits and metalliferous muds and B) Map of Hatiba Mons volcano in the Central Red Sea and recently discovered vent fields and sampling stations of RV Meteor cruise M194.

Our new samples, obtained during M194 at Hatiba Mons by 3m-long gravity cores, provide additional insights into the hydrothermal system. The interior of the Fe-mounds partially consists of euhedral hematite, pyrite, anhydrite, and abundant barite, along with massive sphalerite, as well as anhedral Fe-oxyhydroxides and silicates. The presence of euhedral anhydrite and the paragenetic sequence suggest a waning hydrothermal system that experienced much higher fluid temperatures (i. e., >130-150°C) in the past. A multidisciplinary approach of shore-based research was applied to characterize the sediments and hydrothermal precipitates from the interior of a hydrothermal mound. The establishment of a geochemical and mineralogical framework for this active hydrothermal system in the Red Sea was achieved through the implementation of methods including X-ray fluorescence (XRF), instrumental neutron activation analysis (INAA), inductively coupled plasma mass spectrometry (ICP-MS), X-ray diffraction (XRD), electron-microprobe (EPMA), sulfur isotope analyses, microthermometry, and microscopy. Future whole-genome metagenomic (Illumina NovaSeq 6000, SP150) and morphological (scanning electron microscopy, SEM) analyses will elucidate the role of microbial communities in mound formation and mineral precipitation. Additionally, pore fluid chemistry data will further enhance our understanding of the formation of the hydrothermal system at Hatiba Mons, the processes responsible for the chemical variability within the mounds, and the effect on chemotrophic microbial communities.

Our data provide the first detailed description of the geochemistry and mineralogy of an active hydrothermal vent system in the Red Sea outside the metalliferous muds in brine pools such as those in the Atlantis-II Deep. It is evident from the location of the vent field on top of a mid-ocean ridge (MOR) volcano and from the geochemical and mineralogical signature of the deposit that the hydrothermal precipitates at Hatiba Mons are similar to MOR basalt-hosted deposits elsewhere on the global mid-ocean ridges. However, given the close proximity (<10km) of Miocene evaporites around Hatiba Mons Volcano, the observation of small brine-filled depressions at the top of the volcano does not come as a surprise. This, together with high salinities in fluid inclusions in barite (all above seawater salinity, including fluid inclusions showing halite crystallization), suggests that dissolved Miocene evaporites may play a substantial role in the hydrothermal system, possibly also affecting metal solubility, transport, and precipitation. Microthermometry on fluid inclusions in barite further supports a high-temperature formation of the mounds' interior with homogenization temperatures up to >300°C for barite. At these temperatures, boiling of upwelling hydrothermal fluids at the seafloor could be another driving factor for the high salinities observed. However, no clear evidence of boiling has been documented in fluid inclusions so far. At a water depth of 950m, the absence of Cu-rich precipitates likely indicates that vent temperatures may be a limiting factor for metal precipitation in the present system, possibly suggesting the presence of even higher-temperature deposits at greater depths.

In this study, we provide a preliminary description of the first truly polymetallic massive sulfide occurrence of the Red Sea. The deposit at Hatiba Mons formed at high temperatures, clearly showing that the fundamentals of hydrothermal activity in the Red Sea are not entirely different from other mid-ocean ridges; however, the elevated salinities may provide evidence that the geological setting allows for greater variability in the mineral deposits currently not observed in modern seafloor hydrothermal systems, but common in the fossil rock record. The Red Sea spreading center remains an exploration target for the discovery of further sulfide occurrences and/or high-temperature vent sites. The role of microbes in mound formation and/or degradation will be further investigated. The presence of intermediate- to high-temperature mineral assemblages, current low-temperature fluid venting, and the presence of microbial mats, along with high-temperature precipitates within the mound, suggests a complex and dynamic history of hydrothermal activity at Hatiba Mons volcano and in the Red Sea. These findings contribute to a deeper understanding of the formation of marine mineral deposits, the evolution of hydrothermal systems, and their broader implications for deep-sea geochemistry and microbial ecology.

References

- Augustin N, van der Zwan FM, Petersen S, et al., The Effect of Spreading Rate on the Volcanic Activity and Frequency Distribution of Hydrothermal Vent Sites in the Red Sea, Meteor Cruise Reports, 2023.
- Augustin N, Van Der Zwan FM, Devey CW, et al., Geomorphology of the central Red Sea Rift: Determining spreading processes, *Geomorphology*, 2016, 274, 162–179, doi:10.1016/j.geomorph.2016.08.028.
- Bruneau L, Jerlov NG, Koczy FF, Physical and chemical methods (+ Appendix), Reports of the Swedish deep-sea expedition. 1953, III:99–112.
- Corliss JB, Dymond J, Gordon LI, et al., Submarine Thermal Springs on the Galápagos Rift, *Science*, 1979, 203(4385), 1073–1083, doi:10.1126/science.203.4385.1073.
- Degens ET, Ross DA, eds. Hot Brines and Recent Heavy Metal Deposits in the Red Sea, Springer Berlin Heidelberg, 1969, doi:10.1007/978-3-662-28603-6.
- German CR, Petersen S, Hannington MD, Hydrothermal exploration of mid-ocean ridges: Where might the largest sulfide deposits be forming?, *Chemical Geology*, 2016, 420, 114–126, doi:10.1016/j.chemgeo.2015.11.006.
- Hannington M, Jamieson J, Monecke T, et al., The abundance of seafloor massive sulfide deposits, *Geology*, 2011, 39(12), 1155–1158, doi:10.1130/G32468.1.
- Miller AR, Densmore CD, Degens ET, et al., Hot brines and recent iron deposits in deeps of the Red Sea, *Geochimica et Cosmochimica Acta*, 1966, 30, 341–359.
- van der Zwan FM, Augustin N, Petersen S, et al., Widespread diffuse venting and large microbial iron-mounds in the Red Sea, *Commun Earth Environ*, 2023, 4(1), 496, doi:10.1038/s43247-023-01169-7.
- van der Zwan FM, Devey CW, Augustin N, Almeev RR, Bantan RA, Basaham A, Hydrothermal activity at the ultraslow- to slow-spreading Red Sea Rift traced by chlorine in basalt, *Chemical Geology*, 2015, 405, 63–81, doi:10.1016/j.chemgeo.2015.04.001.

MSM111

Sea ice and ice sheet dynamics in southeastern Baffin Bay from late MIS 3 to early Holocene: A highly-resolved biomarker study

Authors

Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany

M. Mikler, J. Müller, J. Hefter

Department of Geosciences, University of Bremen | Bremen, Germany

J. Müller, C. Vogt, Y. Zhang, T. von Dobeneck, J. Titschak, M. Kucera

MARUM – Center for Marine Environmental Sciences, University of Bremen | Bremen, Germany

J. Müller, J.C. Faust, C. Vogt, Y. Zhang, T. von Dobeneck, J. Titschak, M. Kucera

Crystallography & Geomaterials, FB05 Geosciences, University of Bremen | Bremen, Germany

C. Vogt

Background

Arctic sea ice plays a critical role in the global climate system. Sea ice is, on the one hand, a “symptom” of climate change, but may also act as a modulator of climate change through internal feedbacks, e. g., by indirectly affecting the hydrological cycle. The interrelations among sea ice, ice sheet and ocean dynamics are yet not fully understood. The investigation of past changes in Arctic sea-ice conditions in tandem with ice sheet and ocean dynamics is imperative to improve the understanding of the fate and role of these entangled, critical components of the Earth system.

Several studies applied microfossils (e. g., ostracods, diatoms, dinocysts) as indirect proxies for paleo sea ice in the Arctic. However, the use of these proxies is often complicated by the dissolution or poor preservation of the latter in Arctic

marine sediments. IP25 (“Ice proxy with 25 carbon atoms”) is a biomarker proxy that is produced by sea ice algae during spring melt (Belt et al., 2007). IP25 is quite prone to degradation and its presence in Arctic marine sediments thus indicates the presence of sea ice at the time of deposition (Belt et al., 2007). However, IP25 is not produced in thick, light-blocking sea ice, complicating the differentiation between ice-free conditions and permanent ice cover (Müller et al., 2011). To overcome this difficulty, Müller et al. (2011) refined IP25-based sea-ice reconstructions by combination with open-ocean biomarkers (i. e. brassicasterol, dinosterol). This so-called PIP25 index allows the discrimination of different sea-ice scenarios (e. g., ice-free, marginal sea-ice, lasting sea-ice) (Müller et al., 2011). Smik et al. (2016) further proposed the use of HBI III for PIP25 paleo sea-ice estimates as a more suitable open-ocean counterpart.

Baffin Bay is an ocean basin located between Greenland and Baffin Island and is strongly influenced by seasonal sea ice (Tang et al., 2004). It is located between the central Arctic Ocean and the North Atlantic and is thus a sensitive region to study paleoclimatic changes (Stein, 1991). Some studies reconstructed paleo sea-ice conditions using biomarkers in Baffin Bay, but these are mostly restricted to the Holocene (e. g., Harning et al., 2025; Saini et al., 2020; Saini et al., 2022) and the Last Deglaciation (You, 2023). A study by Jennings et al. (2018) provides a lowly-resolved biomarker record of brassicasterol and IP25 in the southeastern Baffin Bay covering the time interval between ~26–10 ka BP. The authors suggest the presence of perennial sea-ice during the LGM based on the constant presence of brassicasterol in their record and refute the potential existence of an extensive ice shelf in Baffin Bay that has been proposed in earlier studies (e. g., Hughes et al., 1977; Hulbe, 1997). However, several studies report that brassicasterol might have variable sources (e. g., pelagic, freshwater, sea ice, terrigenous) (Belt et al., 2015 and references therein), thus limiting its reliability as an open-ocean phytoplankton proxy.

Material and Methods

In our study, we analyzed core GeoB25212-3 that was taken during Expedition MSM111 in fall 2022 from the continental slope west of Disko Bugt. The ~17 m-long gravity core holds a highly-resolved sediment record spanning from ~32 to 8 ka BP, thus providing insight into a time period of dramatic climate change shortly before, across, and following the Last Glacial Maximum.

Next to the sea-ice proxy IP25, we analyzed several open-ocean phytoplankton biomarkers (i. e. brassicasterol, dinosterol, and HBI III) to obtain comprehensive insights into past sea-ice conditions and past bioproductivity. To obtain information on paleo ice sheet dynamics or terrigenous run-off, we analyzed terrestrial biomarkers, e. g., plant wax lipids, as well as ice rafted debris (IRD)

contents, bulk mineral assemblages, magnetic properties, and the elemental composition of the sediments. Past ocean temperatures were reconstructed by analyzing GDGTs.

Results and Discussion

Our results show that IP25 concentrations were low, while open-ocean biomarker concentrations were relatively high during late MIS 3. This is further accompanied by relatively high subsurface temperatures. We therefore suggest that only minor sea-ice cover was present during the immediate pre-LGM period in southeastern Baffin Bay, and probably associated with an enhanced influx of warm Atlantic-sourced water masses. This is consistent with the findings of an earlier study by Mudie and Aksu (1984). The authors suggest that enhanced influx of Atlantic water and low sea-ice coverage contributed enhanced moisture supply that is necessary for the build-up of the massive glacial ice sheets in the Northern Hemisphere (i. e. Laurentide, Innuitian and Greenland ice sheets).

Toward the LGM, we observe a gradual decline in subsurface temperature in the bay. Around 25–23 ka BP, we observe a shift to high magnetic susceptibility (MS) and Zr/Rb values, potentially indicating the expansion of the Greenland Ice Sheet (GIS) toward the shelf-break. In the aftermath, a shutdown in productivity occurs at our site, indicating the formation of thick, permanent ice coverage in the bay. The thick ice coverage persisted until late Heinrich Stadial 1 around 16 ka BP at our site. However, this is interrupted by a short-lived decline in the ice coverage at the onset of the Last Deglaciation around 18.8 ka BP, characterized by high phytoplankton biomarker concentrations, a decline in MS and Zr/Rb and the first, but subtle, IRD deposition in the record. The final demise of permanent ice coverage around 16 ka BP was preceded and accompanied by an abrupt increase in subsurface temperatures of ~1°C at our site and a shift to low MS and Zr/Rb values, indicating a recession of the GIS (similar to Jennings et al., 2018). Jennings et al. (2017) also report elevated subsurface temperatures around 16.2 ka BP at the western Greenland margin. In the aftermath, enhanced IP25 production and elevated open-ocean phytoplankton productivity indicate a shift to less ice coverage in the bay. This is furthermore accompanied by enhanced IRD deposition at our site, indicating increased ice-sheet instability. During the Bølling-Allerød interstadial and the early Holocene, we identified two Baffin Bay Detrital Carbonate (BBDC) layers based on elevated dolomite contents and Ca/Sr values in our core. These indicate the disintegration of the ice sheet of the North American Arctic ice sheet complex (Jackson et al., 2023). During these BBDC events, IP25 concentration is especially enhanced at our site and might be explained by iceberg-fertilization or freshwater-triggered sea-ice growth. Furthermore, subsurface temperatures are relatively low during BBDC events, indicating a cooling of the subsurface water masses during these catastrophic

discharge events. However, after BBDC 0, we observe an abrupt shift to extensive sea-ice cover at our site.

Conclusions

In contrast to Jennings et al. (2018), our results generally support the potential existence of an ice shelf during the LGM and early HS1 in southeastern Baffin Bay. However, further work is needed to facilitate the unambiguous identification of paleo ice shelves in Baffin Bay.

Overall, ice coverage in Baffin Bay seems to be during the late MIS 3-late HS1 period sensitive to changes in subsurface temperatures, that seems to dominantly follow the trend in summer insolation. From late HS1 onwards, subsurface temperatures, ice coverage, and summer insolation seem to be decoupled. This is likely due to enhanced freshwater release that impacted the water mass characteristics in Baffin Bay during the Last Deglaciation.

References

Belt ST, Cabedo-Sanz P, Smik L, Navarro-Rodriguez A, et al., Identification of paleo Arctic winter sea ice limits and the marginal ice zone: Optimised biomarker-based reconstructions of late Quaternary Arctic sea ice. *Earth Planet Sc Lett* 2015, 431, 127-139, doi: 10.1016/j.epsl.2015.09.020.

Belt ST, Masse G, Rowland SJ, Poulin M, et al., A novel chemical fossil of palaeo sea ice: IP25. *Org Geochem* 2007, 38, 16–27, doi: 10.1016/j.orggeochem.2006.09.013.

Harning D J, Jennings AE, Holman B, Kelleher RV, et al., Spatiotemporal Variability in the Holocene Extent of Pikialasorsuaq (North Water Polynya), Baffin Bay, *Paleoceanography and Paleoclimatology* 2025, 40, doi: 10.1029/2025PA005153.

Hughes T, Denton GH & Grosswald MG, Was there a late-Würm Arctic Ice Sheet?, *Nature* 1977, 266, 596–602, doi: 10.1038/266596a0.

Hulbe CL, An ice shelf mechanism for Heinrich layer production, *Paleoceanography* 1997, 12, 711–717, doi: 10.1029/97PA02014.

Jackson R, Frederichs T, Schulz H & Kucera M, Chronology of detrital carbonate events in Baffin Bay reveals different timing but similar average recurrence time of North.

American-Arctic and Laurentide ice sheet collapse events during MIS 3. *Earth Planet Sc Lett* 2023, 613, 118191, doi: 10.1016/j.epsl.2023.118191.

Jennings AE, Andrews JT & Cofaigh CO, St-Onge G, et al., Baffin Bay paleoenvironments in the LGM and HS1: Resolving the ice-shelf question, *Mar Geol* 2018, 402, 5–16, doi: 10.1016/j.margeo.2017.09.002.

Jennings AE, Andrews JT, Ó Cofaigh C, St-Onge G, et al., Ocean forcing of Ice Sheet retreat in central west Greenland from LGM to the early Holocene, *Earth Planet Sc Lett* 2017, 472, 1–13, doi: 10.1016/j.epsl.2017.05.007.

Mudie PJ & Aksu AE, Palaeoclimate of Baffin Bay from 300,000-year record of foraminifera, dinoflagellates and pollen, *Nature* 1984, 312, 630–634, doi: 10.1038/312630a0.

Müller J, Wagner A, Fahl K, Stein R, et al., Towards quantitative sea ice reconstructions in the northern North Atlantic: A combined biomarker and numerical modelling approach, *Earth Planet Sc Lett* 2011, 306, 137–148, doi: 10.1016/j.epsl.2011.04.011.

Saini J, Stein R, Fahl K, Weiser J, et al., Holocene variability in sea ice and primary productivity in the northeastern Baffin Bay, *Arktos* 2020, 6, 55–73, doi: 10.1007/s41063-020-00075-y.

Saini J, Stein R, Fahl K, Weiser J, et al., Holocene variability in sea-ice conditions in the eastern Baffin Bay-Labrador Sea – A north–south biomarker transect study, *Boreas* 2022, 51, 553–572, doi: 10.1111/bor.12583.

Stein R, Organic carbon accumulation in Baffin Bay and paleoenvironment in high northern latitudes during the past 20 m.y. *Geology* 1991, 19, 356–359, doi: 10.1130/0091-7613(1991)019<0356:Ocaibb>2.3.Co;2.

Tang CCL, Ross CK, Yao T, Petrie B, et al., The circulation, water masses and sea-ice of Baffin Bay. *Prog Oceanogr* 2004, 63, 183–228, doi: 10.1016/j.pocean.2004.09.005.

You D, Last glacial-deglacial variability in sea surface characteristics and ice sheet activities in the Labrador Sea/Baffin Bay, Dissertation 2023, Fachbereich Geowissenschaften, Universität Bremen, Bremen.

MSM111

Mixed Turbidite-Contourite Deposits in an Arctic Gateway: New Insights into the Baffin Bay Basin

Authors

Department of Geosciences, University of Bremen | Bremen, Germany

N. Römer-Stange, T. Schwenk, C. Sun, S. Mukherjee, Y. Zhang, T. von Dobeneck

Department of Geography, Durham University | Durham, United Kingdom

K. Streuff

MARUM – Center for Marine Environmental Sciences | Bremen, Germany

J. Faust, M. Kucera

The Quaternary sediments in the Baffin Bay basin have been described as debrites, turbidites, hemipelagic sediments and ice-rafted-debris shaped by gravity driven processes (Ó Cofaigh et al., 2018; Ownsworth et al., 2023; and references therein). However, new structural imaging and initial coring results acquired during expedition MSM111 with RV ‘Maria S. Merian’ (Kucera et al., 2023) near the Disko Bay Trough Mouth Fan indicate that bottom currents are an additional controlling factor.

The presumed mixed turbidite-contourite deposits are generally complex, and therefore, systematic large scale structural mapping, detailed facies analysis and possibly monitoring is required (Rodrigues et al., 2022). Oceanographic monitoring is sparse in this area, but at depths shallower than 0.6 km the circulation can be described as cyclonic with the northward-flowing West Greenland Current and the southward-flowing Baffin Island Current (Huang et al., 2024). Between ~1.0–1.5 km depth, models and available measurements indicate a southward-flowing counter-current >10cm/s along the Greenland shelf between 68–72°N (Tang et al., 2004). Further south in Davis Strait, southward-flowing currents have shaped a contouritic drift complex since the Miocene (Nielsen et al., 2011) with mean current velocities of 10–30 cm/s (Tang et al., 2004). Drift complexes of Miocene-Pliocene age have also been documented in the Baffin Bay basin (Knutz et al., 2015). At shallower depths on the shelf edge of the Disko Bay Trough Mouth Fan,

the Paleo–West Greenland Current presumably generated contouritic deposits during the Eemian (Hofmann et al., 2016, 2018). In contrast, morphology, seismic facies, and lithofacies along the southwestern-facing section of the Disko Bay Trough Mouth Fan were investigated by Ó Cofaigh et al. (2018), who found no indications of bottom-current influence.

In this study, an area of more than 4000 km² with 100 km north-south extent, and a line spacing of 3–4 km has been investigated at the north-west facing section of the Disko Bay Trough Mouth Fan. The data set comprises Parasound data and swath bathymetry. The Parasound operated at ~4 kHz, giving a decimetre scale vertical resolution, and achieved a maximum penetration of ~100 ms two-way travel time (~75 m). The beam angle was ~4°, yielding a footprint width of ~0.07 × water depth. Steep slopes >2° were poorly imaged due to incidence-angle constraints. Unconformities have been systematically mapped and the reflector configurations as well as the reflector terminations have been analyzed. Those observations were integrated with five gravity cores (cored length 8.6–17 m) from the study area, for which core descriptions and images are available. Subsets additionally include XRF core-scanning data, X-ray CT images, and limited 14-C ages.

The Quaternary sediments in the study area are interpreted to be overprinted by bottom currents, as (1) erosional truncations at the unconformities indicate erosive events; (2) across slope thickness changes of depocenters are observed indicating current velocity changes; (3) onlapping reflectors have been found; (4) slope parallel depressions interpreted as furrows are found in water depths of 0.6–1.1 km. The timing of the unconformities appears broadly consistent with Holocene variability inferred from shelf archives (Hansen et al., 2020; Saini et al., 2022) and ice core records (Wolff et al., 2010). XRF Zr/Al ratios, used here as a proxy for coarser fractions and sediment sorting (Bahr et al., 2014), show trends consistent with enhanced bottom-current activity, although provenance and IRD input may also influence this signal. Gravity-driven mass-transport deposits are also present, as indicated by acoustically transparent layers, slide scars, and age inversions in cores. Therefore, it is concluded that the sediment bodies formed in a mixed turbiditic–contouritic system. The investigated, north-western face of the Disko Bay Trough Mouth Fan seems to be morphologically different from the south-western face. Ó Cofaigh et al. (2018) report gullies and turbiditic as well as hemipelagic deposits for the southern section. This difference may be due to sheltering from currents by the shape of the fan. Possibly, the current influence in the south is also more subtle and could only be revealed by more detailed mapping of the sediment bodies.

To our knowledge, this study provides the first description of Late Pleistocene to modern contouritic deposits in the Baffin Bay basin. Unlocking this archive offers the opportunity to reconstruct bottom currents during the Late Pleistocene and

Holocene in a key location for Arctic–Atlantic exchange. More broadly, studying this modern system in Baffin Bay can inform interpretations of contourite systems in the geologic record and their role in sediment focusing and organic carbon burial. Mixed turbiditic–contouritic deposits are also relevant to slope stability and to evaluating hydrocarbon and Carbon Capture and Storage sites (Rodrigues et al., 2022). Finally, improved process understanding will enable better correlation among cores in the study area and with basin-wide events such as the Baffin Bay Detrital Carbonate layers.

References

- Bahr A, Jiménez-Espejo FJ, Kolasinac N, Grunert P, Hernández-Molina FJ, Röhl U, et al., Deciphering bottom current velocity and paleoclimate signals from contourite deposits in the Gulf of Cádiz during the last 140 kyr: An inorganic geochemical approach, *Geochemistry, Geophysics, Geosystems* 2014, 15(8), 3145–3160. <https://doi.org/10.1002/2014GC005356>.
- Hansen KE, Giraudeau J, Wacker L, Pearce C & Seidenkrantz M-S, Reconstruction of Holocene oceanographic conditions in eastern Baffin Bay, *Climate of the Past* 2020, 16(3), 1075–1095, <https://doi.org/10.5194/cp-16-1075-2020>.
- Hofmann JC, Knutz PC, Nielsen T & Kuijpers A, Seismic architecture and evolution of the Disko Bay trough-mouth fan, central West Greenland margin, *Quaternary Science Reviews* 2016, 147, 69–90, <https://doi.org/10.1016/j.quascirev.2016.05.019>.
- Hofmann JC, Knutz PC, Kjær KH, Nielsen T & Ó Cofaigh C, Glacial and submarine processes on the shelf margin of the Disko Bay Trough Mouth Fan, *Marine Geology* 2018, 402, 33–50. <https://doi.org/10.1016/j.margeo.2017.12.001>.
- Huang J, Pickart RS, Bahr F, McRaven LT, Tremblay J-É, Michel C, et al., Water mass evolution and general circulation of Baffin Bay: Observations from two shipboard surveys in 2021, *Progress in Oceanography* 2024, 229, 103322, <https://doi.org/10.1016/j.pocean.2024.103322>.
- Knutz PC, Hopper JR, Gregersen U, Nielsen T & Japsen P, A contourite drift system on the Baffin Bay–West Greenland margin linking Pliocene Arctic warming to poleward ocean circulation, *Geology* 2015, 43(10), 907–910, <https://doi.org/10.1130/G36927.1>.

Kucera M, Faust JC, Meilland J, DMello G, Janßen A, von Dobeneck T, et al., Deep drilling in the Baffin Bay for marine sediment records of Greenland Ice Sheet collapse during past warm intervals, Cruise No. MSM111, 02.09.–04.10.2022, Reykjavik (Iceland) – St. John's (Canada), MARIA S. MERIAN-Berichte 2023), pp. 1–69), Bonn, https://doi.org/10.48433/cr_msm111.

Nielsen T, Andersen C, Knutz PC, & Kuijpers A, The Middle Miocene to Recent Davis Strait Drift Complex: implications for Arctic–Atlantic water exchange, *Geo-Marine Letters* 2011, 31(5), 419–426, <https://doi.org/10.1007/s00367-011-0245-z>.

Ó Cofaigh C, Hogan KA, Jennings AE, Callard SL, Dowdeswell JA, Noormets R & Evans J, The role of meltwater in high-latitude trough-mouth fan development: The Disko Trough-Mouth Fan, West Greenland, *Marine Geology* 2018, 402, 17–32, <https://doi.org/10.1016/j.margeo.2018.02.001>.

Owensworth E, Selby D, Lloyd J, Knutz P, Szidat S, Andrews J & Ó Cofaigh C, Tracking sediment delivery to central Baffin Bay during the past 40 kyrs: Insights from a multiproxy approach and new age model, *Quaternary Science Reviews* 2023, 308, 108082, <https://doi.org/10.1016/j.quascirev.2023.108082>.

Rodrigues S, Hernández-Molina FJ, Fonnesu M, Miramontes E, Rebesco M & Campbell DC, A new classification system for mixed (turbidite-contourite) depositional systems: Examples, conceptual models and diagnostic criteria for modern and ancient records, *Earth-Science Reviews* 2022, 230, 104030, <https://doi.org/10.1016/j.earscirev.2022.104030>.

Saini J, Stein R, Fahl K, Weiser J, Hebbeln D & Madaj L, Holocene variability in sea-ice conditions in the eastern Baffin Bay-Labrador Sea – A north–south biomarker transect study, *Boreas* 2022, 51(3), 553–572, <https://doi.org/10.1111/bor.12583>.

Tang CCL, Ross CK, Yao T, Petrie B, DeTracey BM & Dunlap E, The circulation, water masses and sea-ice of Baffin Bay, *Progress in Oceanography* 2004, 63(4), 183–228, <https://doi.org/10.1016/j.pocean.2004.09.005>.

Wolff EW, Chappellaz J, Blunier T, Rasmussen SO & Svensson A, Millennial-scale variability during the last glacial: The ice core record, *Quaternary Science Reviews* 2010, 29(21), 2828–2838, <https://doi.org/10.1016/j.quascirev.2009.10.013>.

MSM111

Multiproxy paleoenvironmental reconstruction in the Narsaq Sound over the last 12,000 years

Authors

MARUM – Centre for marine environmental sciences, University of Bremen | Bremen, Germany

J.C. Faust, R. Jackson, R. Morard, L. Wörmer, M. Siccha, M. Kucera

Faculty of Geosciences, University of Bremen | Bremen, Germany

J. Müller,

GEOTOP, Université du Québec à Montréal | Montréal, Canada

A. de Vernal, E. Folie-Voivin,

Alfred Wegener Institute Helmholtz Centre for Marine and Polar Research (AWI) | Bremerhaven, Germany

N. V. Jäger, A. Janßen,

GeoGenetics, Globe Institute, University of Copenhagen | Copenhagen, Denmark

M. Menéndez-Serra, A. Fernandez-Guerra, L. Vinner, T. S. Korneliussen, E. Willerslev

Department of Earth Sciences, Aarhus University | Aarhus, Denmark

M. Toplak,

University of Toulouse, LEGOS (CNES, CNRS, IRD, UT) | Toulouse, France

F. Léger

Sediments accumulating in Greenlandic fjords, positioned at the critical interface between the ice sheet and the ocean, provide exceptional archives for studying environmental responses to past climate variability and associated organic carbon dynamics. These fjord systems are particularly sensitive to changes in glacier dynamics, sea ice extent, ocean circulation, and terrestrial inputs, making them ideal for reconstructing centennial-to-millennial scale climate fluctuations and their impacts on both marine and terrestrial ecosystems. Understanding past environmental changes in these systems is crucial for contextualizing the impacts of ongoing and future climate change in the Arctic.

In this study, we present a comprehensive multiproxy analysis of a remarkably well-preserved sedimentary record from Narsaq Sound in southern Greenland, a region of particular historical and paleoclimatic significance due to its proximity to the former Norse Eastern Settlement. The sediment sequence, comprising an approximately 30 cm multicore recovered on top of an approximately 11-meter gravity core (GeoB25206-2), was collected from 285 meters water depth during the MSM111 expedition in September 2022. High-resolution radiocarbon dating performed on mixed benthic foraminifera assemblages indicates a maximum age of approximately 12,000 years, spanning from the last deglaciation through the entire Holocene. The age-depth model reveals a relatively constant sedimentation rate of approximately 1 meter per thousand years, providing exceptional temporal resolution for paleoenvironmental reconstruction, particularly for the last millennium.

Our analytical approach integrates multiple complementary methods to reconstruct past environmental conditions. Non-destructive whole-core analyses included magnetic susceptibility measurements, X-ray fluorescence (XRF) elemental scanning, and high-resolution computer tomography (CT) scanning for detailed sedimentological characterization and quantification of ice-rafted debris (IRD). Discrete sediment samples were systematically collected at 5–10 cm intervals from the gravity core and at 1 cm resolution from the multicore, enabling high-resolution analysis of the most recent environmental changes. These samples were analyzed for total organic carbon (Corg) using LECO analysis, total nitrogen content via elemental analyzer isotope ratio mass spectrometry, and stable isotope compositions ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$) to trace organic matter sources and cycling. Biomarker analyses, including the sea ice proxy IP_{25} and various phytoplankton sterols such as brassicasterol, were performed using gas chromatography-mass spectrometry to reconstruct past sea ice conditions and marine productivity. Ancient DNA analyses were employed to reconstruct past ecosystems and detect specific taxa including seals. Additionally, organic carbon lability was assessed to understand carbon burial efficiency and diagenetic processes. Pore water samples extracted from the cores were examined for elemental composition and dissolved organic carbon concentrations to characterize early diagenetic processes and biogeochemical cycling.

Preliminary results reveal distinct sedimentological features and compositional changes that reflect major shifts in regional environmental conditions linked to nearby glacier dynamics and large-scale Holocene climate transitions, particularly the shift from the Medieval Climate Anomaly (MCA; ~850–1250 CE) to the Little Ice Age (LIA; 1600–1850 CE). The presence and distribution of ice-rafted debris and variations in bioturbation intensity provide direct evidence of changing glacier and iceberg activity, as well as shifts in benthic ecosystem functioning. Notably, the element niobium (Nb), which is sourced from the local bedrock catchment, emerges as a highly promising geochemical tracer of terrigenous sediment supply

and hydroclimate variability. A pronounced decline in niobium content during the transition from the MCA to the LIA indicates a long-term shift from wetter to drier conditions, likely driven by changes in atmospheric circulation patterns, specifically a transition from predominantly positive to negative North Atlantic Oscillation (NAO) states. This drying trend is consistent with independent snow accumulation records from coastal West Greenland and lacustrine biomarker data from nearby lakes.

A marked compositional shift in the sedimentary organic carbon pool is observed during the deglaciation–thermal maximum transition, characterized by a change from predominantly terrestrial to marine organic carbon sources, as indicated by decreasing Corg/N ratios. Marine sources continue to dominate throughout the remainder of the Holocene, though with notable variations in accumulation rates and composition that reflect changes in marine productivity and terrigenous input. Biomarker analyses reveal a critical environmental threshold around 1300 CE, when substantial sea ice presence emerged in the Narsaq Sound region, as indicated by elevated IP₂₅ concentrations. This sea ice expansion persisted intermittently until approximately 1630 CE and coincides with a dramatic increase in IRD deposition, reduced bioturbation activity suggesting diminished benthic ecosystem functioning, and a pronounced shift toward cold-water dinoflagellate cyst taxa typically associated with sea ice conditions. These changes reflect enhanced influence of the cold, low-salinity East Greenland Current and increased iceberg calving from advancing tidewater glaciers and the Greenland Ice Sheet.

Ancient DNA analyses concentrated on the last 1000 years provide unprecedented insights into ecosystem composition during the period of Norse occupation of the fjord region. The DNA record reveals relative stability in marine and terrestrial community composition through much of this interval. Critically, however, seal DNA, which is present in earlier samples, completely disappears from the sediment record between approximately 1350 and 1630 CE, coincident with the period of enhanced sea ice presence. This finding correlates remarkably with archaeological evidence showing a dramatic dietary shift among the Norse population – from approximately 80% terrestrial resources at the time of settlement establishment to up to 80% marine resources (particularly seals) by the final phase of occupation – and changes in hunted seal species composition between 1250 and 1300 CE. The sudden disappearance of the Norse population from the Narsaq Sound region in the early 15th century coincides temporally with this interval of maximum sea ice influx and seal DNA absence, suggesting that the combined effects of extensive sea ice cover, increased iceberg hazards, and associated ecosystem changes severely constrained maritime communication, resource access, and ultimately the viability of the settlement.

Our findings demonstrate that the Narsaq Sound sediment record offers an exceptionally high-resolution, multiproxy archive of past glacial activity,

hydroclimate variability, sea ice dynamics, and ecosystem change. This study provides crucial new insights into how large-scale climate variability – driven by changes in solar activity, volcanic forcing, atmospheric circulation patterns, and ocean dynamics – has shaped local environmental conditions in southern Greenland since the last deglaciation. Furthermore, our results highlight the sensitivity of Arctic fjord systems and human societies to abrupt climate shifts, offering important context for understanding potential responses to ongoing and future climate change in these vulnerable regions.

MSM111

Continuous reproduction of planktonic foraminifera in laboratory culture

Authors

Center for Marine Environmental Sciences, University of Bremen | Bremen, Germany

J. Meilland, M. Sicca, R. Morard, M. Kucera

Planktonic foraminifera are marine protists that play crucial roles in oceanic ecosystems and serve as essential paleoclimatic proxies due to the geochemical signatures preserved in their calcareous shells. Despite their importance, our understanding of their life cycles and reproduction strategies has remained incomplete, primarily because most species cannot be maintained in long-term laboratory culture. For decades, planktonic foraminifera were considered obligate sexual outbreeders, reproducing primarily through gametogenesis. However, recent observations have revealed that nonspinose species can also reproduce via multiple fission, a form of asexual reproduction that produces numerous offspring from a single parent cell. While the frequency of multiple fission in natural populations appears relatively low (approximately 3%), the survival rate of the offspring is remarkably high, and critically, specimens approaching fission exhibit distinguishable morphological traits including thin, translucent shells with highly spherical chambers and intense cytoplasmic coloration.

Building upon these observations, we developed and optimized a comprehensive culturing protocol specifically designed to enhance both the detection and frequency of fission events in laboratory conditions. This protocol encompasses all stages from shipboard sampling to long-term laboratory maintenance, including careful specimen selection based on morphological indicators, controlled feeding regimes using live diatom cultures, and systematic twice-daily monitoring using inverted microscopy. The protocol can be implemented by small teams during oceanographic expeditions and is adaptable to various marine research settings.

We applied this optimized protocol to specimens of *Neogloboquadrina pachyderma* collected from six stations across the Irminger Sea, Labrador Sea, and Baffin Bay during the MSM111 expedition in autumn 2022. A total of 312 specimens were collected and placed in culture. Importantly, we employed two

sampling strategies: random selection based solely on the presence of cytoplasm (192 specimens), and selective picking targeting individuals displaying the previously identified morphological traits associated with impending fission (120 specimens). This comparative approach allowed us to quantitatively assess the effectiveness of trait-based selection. The results were striking: while only 2% of randomly selected specimens reproduced via fission, nearly 60% of selectively picked specimens underwent multiple fission, demonstrating that the reproductive mode can be predicted from shell morphology and that specimens destined for fission can be reliably identified and enriched in culture.

The 29 fission events observed during the expedition produced over 3,000 offspring, which we successfully maintained in laboratory culture following their transport to Germany. To optimize offspring growth and survival, we conducted feeding experiments using four different strains of live diatoms (*Phaeodactylum tricornutum*, *Thalassiosira weissflogii*, *Chaetoceros debilis*, and *Pseudonitzschia turgidula*) known to occur in North Atlantic and Arctic waters. Our results revealed that diet quality, rather than quantity, was the primary factor controlling offspring growth rates. Specimens fed with *Pseudonitzschia turgidula* showed the fastest growth and highest survival, with some individuals reaching adult size (>80 μm , >10 chambers) and surviving up to seven months in culture. Proloculus measurements confirmed that all offspring possessed megalospheric proloculi (large first chambers), consistent with production via multiple fission rather than sexual reproduction.

Most significantly, during the subsequent six months of culturing, we documented second-generation reproduction in seven lineages and third-generation reproduction in two lineages, all occurring via multiple fission. These successive generations of asexual reproduction confirm the existence of a schizont phase in the life cycle of *N. pachyderma*, analogous to that documented in benthic foraminifera. The consistency of megalospheric proloculi across generations indicates that this process represents true clonal reproduction, providing definitive evidence for schizogony in planktonic foraminifera. Interestingly, we observed that approximately 11% of offspring displayed right-coiling (the “aberrant” form), regardless of parental coiling direction, suggesting that reproduction via multiple fission may introduce coiling direction variability into populations.

To test whether our approach could be generalized to other planktonic foraminifera clades, we applied similar culturing strategies to *Globigerinita glutinata* specimens collected from the Gulf of Aqaba in spring 2023. From 130 cultured specimens, we successfully observed two reproductive events via multiple fission, producing viable offspring that grew and added chambers in culture, demonstrating that multiple fission and potentially schizogony occur across different lineages of nonspinose planktonic foraminifera.

This work fundamentally advances our understanding of planktonic foraminifera life cycles by confirming the existence of an optional schizont phase in their reproduction and demonstrating that continuous, multi-generational laboratory culture is achievable. The ability to maintain these organisms through multiple generations under controlled conditions opens unprecedented opportunities for experimental research, including studies of biomineralization, environmental adaptation, stable isotope incorporation, and responses to ocean acidification and warming. Furthermore, our optimized protocol provides a reproducible framework that can be applied to other species and research questions, potentially enabling the establishment of permanent laboratory cultures of these important marine microorganisms. These advances represent a significant step toward overcoming the long-standing barrier of culturing planktonic foraminifera and promise to accelerate progress in foraminiferal biology, ecology, and paleoceanography.

MSM120

Holocene sea-ice and productivity changes on the Scotian Shelf, NW Atlantic

Authors

Institute of Geosciences, Kiel University | Kiel, Germany

P. Matzerath, H. Kolling, R. R. Schneider, F. Gross

Department of Oceanography, Dalhousie University | Halifax, Canada

M. Kienast

Alfred Wegener Institute (AWI) Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany

K. Fahl, R. Stein

Faculty of Geosciences and Centre for Marine Environmental Sciences (MARUM) | Bremen, Germany

R. Stein

Frontiers Sciences Center for Deep Ocean Multispheres and Earth System, and Key Laboratory of Marine Chemistry Theory and Technology, Ocean University of China | Qingdao, China

R. Stein

Center for Ocean and Society, University of Kiel | Kiel, Germany

F. Gross

Importance of the Scotian Shelf and sea-ice reconstructions

The Scotian Shelf is particularly sensitive to ocean and climate changes as it lies near the competing influence of cold polar waters and warm Gulf Stream (GS)-influenced waters (Figure 1; Drinkwater, 1996). During the past two decades, bottom water temperature and salinity in the region have experienced significant variability in response to prevailing North Atlantic Oscillation (NAO) anomalies (Petrie, 2007). Projections indicate that future ocean warming on the Scotian Shelf will exceed average oceanic trends (Saba et al., 2016), posing substantial risks

for both regional marine ecosystems and Northern Hemisphere climate (e. g., Lotze et al., 2022). Despite this paleoenvironmental significance, major gaps in our understanding of past and present ocean and climate dynamics on the Scotian Shelf persist, particularly in terms of sea ice and marine productivity.

Sea ice is a critical component of the ocean-climate system, controlling oceanic physical properties, such as stratification, ventilation and deep water formation, and marine ecosystem dynamics via the control of light availability and nutrient release (e. g., Thomas & Dieckmann, 2010; Meier et al., 2011). To evaluate to what extent the ongoing retreat of sea ice (e. g., Liu et al., 2025) is related to natural variations, it is necessary to reconstruct variations in key parameters such as sea ice and marine productivity over millennial timescales and beyond using proxy records. The only prior sea-ice reconstructions on the Scotian Shelf are dinocyst-based (e. g., Levac, 2001; de Vernal & Hillaire-Marcel, 2006). These are only indirectly related to sea ice (e. g., de Vernal et al., 2013) and therefore remain controversial (e. g., Pieńkowski et al., 2017). The semi-quantitative reconstruction of past sea-ice distributions has been significantly revised by a biomarker-based approach using specific highly branched isoprenoids (HBIs), such as IP₂₅ (ice-proxy with 25 carbon atoms; Belt et al., 2007), which may be key in reconstructing sea-ice conditions on the Scotian Shelf region.

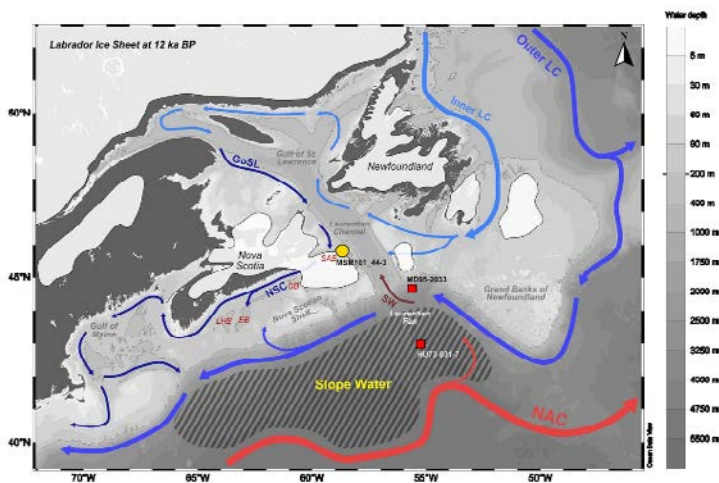


Figure 1: Schematic surface circulation along the eastern Canadian margin (modified after Drinkwater, 1996) with the reconstructed position of the Laurentide Ice Sheet at 12 ka BP (white areas; Shaw et al., 2006). The Nova Scotia shelf and slope is bathed by Nova Scotia Slope Waters as a result of converging warm and cold-water masses originating from the Gulf Stream and the Labrador Current, respectively (LC: Labrador Current; NSC: Nova Scotia Current; GoSL: Gulf of St. Lawrence waters; NAC: North Atlantic Current; SW: Slope Water inflow). Major sedimentary basins on the Scotian Shelf are, from north to south, the St. Anns Basin (SAB), the Canso Basin (CB), the Emerald Basin (EB) and the La Have Basin (LHB). The yellow circle marks the location of core MSM101_44-3 (this study), while red squares indicate other core sites cited in this work: MD95-2033 (de Vernal and Hillaire-Marcel, 2006); HU73-031-7 (Keigwin & Jones, 1995).

Holocene environmental conditions on the Scotian Shelf

In this study we present the combined use of biomarkers, specifically the sea-ice proxy IP₂₅ and spring sea-ice index PIP25 (Müller et al., 2011), together with biomarkers for productivity (i. e., dinosterol, total organic carbon) and terrigenous input (campesterol) in a sediment core from the St. Anns Basin (SAB) located on the northeastern Scotian Shelf (Figure 1) to resolve Holocene changes in sea ice and marine productivity. Our record reveals that spring sea ice on the Scotian Shelf gradually decreased from 10 until 7.5 ka BP, increased between 7.5 and 6.0 ka BP, was reduced overall between 6.0 and 2.5 ka BP, and gradually intensified again from 2.5 to 0.2 ka BP. We could link increased spring sea-ice conditions on the NE Scotian Shelf to significant meltwater inputs originating from the retreat of the Northern Hemisphere ice sheets during the Early Holocene. At around 7.5 ka BP, we could identify an environmental switch from predominantly sympagic towards pelagic marine productivity, which might be associated with a rise in regional relative sea level (Vacchi et al., 2018) and highlight a transition toward a warmer postglacial marine setting on the Scotian Shelf. A short period of extensive spring sea-ice conditions around 6.8 ka BP intersects this transition. It might be connected to the 7.1 ka BP cooling event recorded in several marine records on the Scotian Shelf and Sope regions (Keigwin & Jones, 1995; de Vernal & Hillaire-Marcel, 2006), which could be related to a northwest Atlantic meltwater pulse during that time. Moreover, our record reveals a tight coupling between spring sea ice and marine productivity on the Scotian Shelf with variations in the strength and dominance of the two main water masses (Gulf of St. Lawrence outflow and Labrador Current). Changes associated with positive/negative NAO-phases (Olsen et al., 2012) could have promoted the increase/decrease in spring sea-ice concentration on the Scotian Shelf during the past 5.2 ka BP, similar to records off NE Newfoundland spanning the last 200 years (Weckström et al., 2013).

References

- Belt ST, Massé G, Rowland SJ, Poulin M, et al., A novel chemical fossil of palaeo sea ice: IP₂₅, *Organic Geochemistry* 2007, 38(1), 16–27, doi: <https://doi.org/10.1016/j.orggeochem.2006.09.013>.
- de Vernal A & Hillaire-Marcel C, Provincialism in trends and high frequency changes in the northwest North Atlantic during the Holocene, *Global and Planetary Change* 2006, 54(3–4), 263–290, doi: <https://doi.org/10.1016/j.gloplacha.2006.06.023>.

de Vernal A, Gersonde R, Goosse H, Seidenkrantz, M-S, et al., Sea ice in the paleoclimate system: the challenge of reconstructing sea ice from proxies – an introduction, *Quaternary Science Reviews* 2013, 79, 1–8, doi: <https://doi.org/10.1016/j.quascirev.2013.08.009>.

Drinkwater KF, Atmospheric and Oceanic Variability in the Northwest Atlantic During the 1980s and Early 1990s, *Journal of Northwest Atlantic Fishery Science* 1996, 18, 77–97, doi: <https://doi.org/10.2960/J.v18.a6>.

Lotze HK, Mellon S, Coyne J, Betts M, et al., Long-term ocean and resource dynamics in a hotspot of climate change, *Facets* 2022, 7, 1142–1184, doi: <https://doi.org/10.1139/facets-2021-0197>.

Keigwin LD & Jones GA, The marine record of deglaciation from the continental margin off Nova Scotia, *Paleoceanography* 1995, 10(6), 973–985, doi: <https://doi.org/10.1029/95PA02643>.

Levac E, High resolution Holocene palynological record from the Scotian Shelf, *Marine Micropaleontology* 2001, 43(3-4), 179–197, doi: [https://doi.org/10.1016/s0377-8398\(01\)00033-0](https://doi.org/10.1016/s0377-8398(01)00033-0).

Liu Y, Tang Q, Leung LR, Chen D, et al., Changes in atmospheric circulation amplify extreme snowfall fueled by Arctic sea ice loss over high-latitude land, *Weather and Climate Extremes* 2025, 50, 100802, doi: <https://doi.org/10.1016/j.wace.2025.100802>.

Meier WN & Stroeve J, An Updated Assessment of the Changing Arctic Sea Ice Cover, *Oceanography* 2022, 35(3/4), 10–19, doi: <https://doi.org/10.5670/oceanog.2022.114>.

Müller J, Wagner A, Fahl K, Stein R, et al., Towards quantitative sea ice reconstructions in the northern North Atlantic: A combined biomarker and numerical modelling approach, *Earth and Planetary Science Letters* 2011, 306(3), 137–148, doi: <https://doi.org/10.1016/j.epsl.2011.04.011>.

Olsen J, Anderson NJ & Knudsen MF, Variability of the North Atlantic Oscillation over the past 5,200 years, *Nature Geoscience* 2012, 5(11), 808–812, doi: <https://doi.org/10.1038/ngeo1589>.

Petrie B, Does the north Atlantic oscillation affect hydrographic properties on the Canadian Atlantic continental shelf? *Atmosphere-Ocean* 2007, 45(3), 141–151, doi: <https://doi.org/10.3137/ao.450302>.

Pieńkowski AJ, Gill NK, Furze MF, Mugo SM, et al., Arctic sea-ice proxies: Comparisons between biogeochemical and micropalaeontological reconstructions in a sediment archive from Arctic Canada, *The Holocene* 2017, 27(5), 665–682, doi: <https://doi.org/10.1177/0959683616670466>.

Saba VS, Griffies SM, Anderson WG, Winton M, et al., Enhanced warming of the Northwest Atlantic Ocean under climate change, *Journal of Geophysical Research: Oceans* 2016, 121(1), 118–132, doi: <https://doi.org/10.1002/2015jc011346>.

Shaw J, Piper DJW, Fader GBJ, King EL, et al., A conceptual model of the deglaciation of Atlantic Canada, *Quaternary Science Reviews* 2006, 25(17–18), 2059–2081, doi: <https://doi.org/10.1016/j.quascirev.2006.03.002>.

Thomas DN & Dieckmann G, *Sea Ice* 2nd Edition. UK: Wiley-Blackwell 2010.

Vacchi M, Engelhart SE, Nikitina D, Ashe EL, et al., Postglacial relative sea-level histories along the eastern Canadian coastline, *Quaternary Science Reviews* 2018, 201, 124–146, doi: <https://doi.org/10.1016/j.quascirev.2018.09.043>.

Weckström K, Massé G, Collins LG, Hanhijärvi S, et al., Evaluation of the sea ice proxy IP25 against observational and diatom proxy data in the SW Labrador Sea, *Quaternary Science Reviews* 2013, 79, 53–62, doi: <https://doi.org/10.1016/j.quascirev.2013.02.012>.

PS130/1, PS130/2, PS131, PS132, PS134, PS135/1, PS135/2, PS137, PS140 and MSM111

Seafloor mapping and bathymetric data collection by the AWI Bathymetry group in the time period 2022 to 2024

Authors

**Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research |
Bremerhaven, Germany**

Y. Schulze Tenberge, S. Dreutter, B. Dorschel

World maps give the impression that the global seabed is fully mapped. This is misleading as, according to the General Bathymetric Chart of the Oceans (GEBCO), the authoritative map of the oceans, only about 27.3% of the global seabed has been mapped to modern standards (GEBCO Bathymetric Compilation Group 2025, 2025). In this context, mapped means that the depth of the seabed is directly measured with echosounders resulting in resolutions of tens to hundreds of metres. In unmapped areas, often referred to as “gaps in the map”, depth information for the seabed is interpolated from satellite derived predicted bathymetry with corresponding low resolutions of several kilometres (Figure 1).

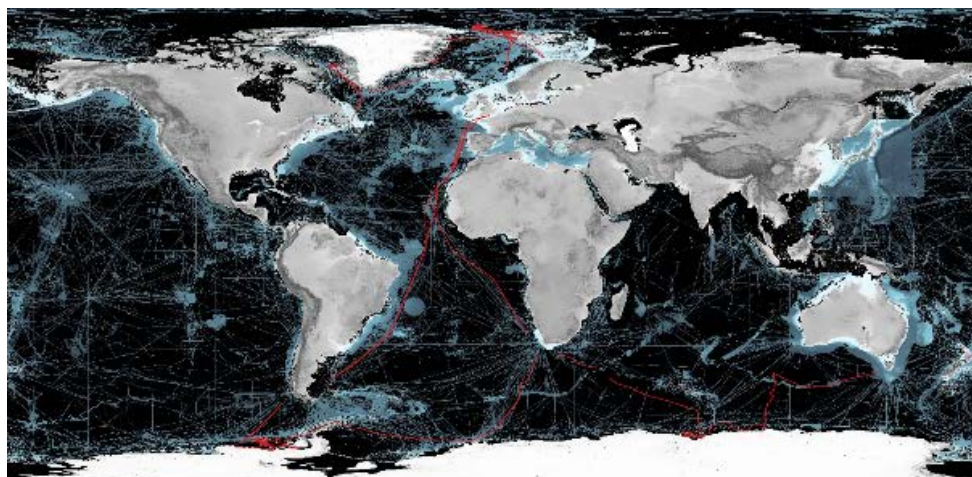


Figure 1: This map visualizes the current state of global bathymetric data coverage as compiled by GEBCO for its 2025 grid. Highlighted in red are bathymetric data collected by the AWI Bathymetry group between 2022 and 2024. Regions rendered in blue shaded relief are constrained by directly measurements using echo sounders, providing high-resolution bathymetry, while in black areas, seafloor depths are derived from indirect measurements, primarily satellite gravity data, with corresponding low spatial resolution. The image highlights the uneven distribution of high-quality seafloor mapping across the world's oceans, with significant gaps still remaining.

This rudimentary state of resolution and coverage of global bathymetric data is outlined in Mayer et al. (2018) and the associated challenges addressed by Wölfl et al. (2019). At the same time, there is an increasing need for high-quality bathymetric information for e. g. cruise planning, for the interpretation of point measurements in a spatial context, and for conservation and management planning – just to name a few.

Collected over years, bathymetric data can also form the basis for regional bathymetric compilations. Examples are the International Bathymetric Chart of the Arctic Ocean (Jakobsson et al., 2024), the International Bathymetric Chart of the Southern Ocean (Dorschel et al., 2022), the Southwest Indian Ocean Bathymetric Compilation (Dorschel et al., 2018), and the Digital Bathymetric Model of the Drake Passage (Bohoyo et al., 2019). These compilations are widely used in many scientific disciplines, are cited in numerous publications, and nicely illustrate the benefit of continuously collected high-quality bathymetric data.

Since 1984, the Alfred Wegener Institute collects bathymetry data with RV Polarstern (Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, 2017) in polar regions and during transit expeditions. Moreover, since 2017, the AWI Bathymetry group collects bathymetric transit data with offset cruise tracks thus allowing for the collection of bathymetric data from previously uncharted seabed.

Between 2022 and 2024, the AWI Bathymetry group collected new bathymetric data during 10 research cruises (PS130/1, PS130/2, PS131, PS132, PS134, PS135/1, PS135/2, PS137, PS140, and MSM111), covering a total area of 718,388 square kilometers (Figure 1). The raw and processed datasets from these expeditions are publicly archived on PANGAEA (Dorschel et al., 2023; Dreutter et al., 2023a, b, c, d, e, f; Schlindwein et al., 2023; Schulze Tenberge et al., 2023a, b, c, d, e, f, 2024a, b; Warnke et al., 2023, 2024). In addition to open access publication, the AWI Bathymetry group provides spatial coverage metadata to the IHO Data Centre for Digital Bathymetry (DCDB) as a Web Map Service (WMS), and delivers processed datasets to the Nippon Foundation – GEBCO Seabed 2030 project. The complete coverage of AWI-collected bathymetric data can be viewed online in the marine-data mapviewer: <https://marine-data.de/viewers/383a79fa-c597-40cc-8a9e-a1d625a241ef>. Through these efforts, AWI contributes to the international goal of achieving comprehensive, high-resolution mapping of the global seafloor by 2030.

References

Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Polar Research and Supply Vessel POLARSTERN Operated by the Alfred-Wegener-Institute, *Journal of large-scale research facilities* 2017, 3, A119, <https://doi.org/10.17815/jlsrf-3-163>.

Bohoyo F, Larter RD, Galindo-Zaldívar J, Leat PT, et al., Morphological and geological features of Drake Passage, Antarctica, from a new digital bathymetric model, *Journal of Maps* 2019, 15, 49–59, <https://doi.org/10.1080/17445647.2018.1543618>.

Dorschel B, Jensen L, Arndt JE, Brummer G -J., et al., The Southwest Indian Ocean Bathymetric Compilation (swIOBC), *Geochem Geophys Geosyst* 2018, 19, 968–976, <https://doi.org/10.1002/2017GC007274>.

Dorschel B, Hehemann L, Viquerat S, Warnke F, et al., The International Bathymetric Chart of the Southern Ocean Version 2, *Scientific Data* 2022, 9, 275, <https://doi.org/10.1038/s41597-022-01366-7>.

Dorschel B, Streuff KT, D’Mello G, Dreutter S, et al., Multibeam bathymetry raw data (Kongsberg EM122 entire dataset) of RV MARIA S. MERIAN during cruise MSM111, PANGAEA 2023, <https://doi.org/10.1594/PANGAEA.953855>.

Dreutter S, Brehmer-Moltmann J, Dorschel K, Dorschel B, et al., Multibeam bathymetry processed data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS134, Bellingshausen Sea, Southern Ocean, PANGAEA 2023a, <https://doi.org/10.1594/PANGAEA.961243>.

Dreutter S, Brehmer-Moltmann J, Dorschel K, Dorschel B, et al., Multibeam bathymetry raw data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS134, PANGAEA 2023b, <https://doi.org/10.1594/PANGAEA.958669>.

Dreutter S, Werner E, Dorschel B, Multibeam bathymetry processed data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS130/1, Atlantic Ocean, PANGAEA 2023c, <https://doi.org/10.1594/PANGAEA.954627>.

Dreutter S, Werner E, Dorschel B, Multibeam bathymetry processed data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS130/2, Atlantic Ocean, PANGAEA 2023d, <https://doi.org/10.1594/PANGAEA.961239>.

Dreutter S, Werner E, Dorschel B, Multibeam bathymetry raw data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS130/1, PANGAEA 2023e, <https://doi.org/10.1594/PANGAEA.951228>.

Dreutter S, Werner E, Dorschel B, Multibeam bathymetry raw data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS130/2, PANGAEA 2023f, <https://doi.org/10.1594/PANGAEA.951226>.

GEBCO Bathymetric Compilation Group 2025, The GEBCO_2025 Grid - a continuous terrain model for oceans and land at 15 arc-second intervals, 2025, <https://doi.org/10.5285/37C52E96-24EA-67CE-E063-7086ABC05F29>.

Jakobsson M, Mohammad R, Karlsson M, Salas-Romero S, et al., The International Bathymetric Chart of the Arctic Ocean Version 5.0. *Scientific Data* 2024, 11, 1, <https://doi.org/10.1038/s41597-024-04278-w>.

Mayer L, Jakobsson M, Allen G, Dorschel B, et al., The Nippon Foundation—GEBCO Seabed 2030 Project: The Quest to See the World's Oceans Completely Mapped by 2030, *Geosciences* 2018, 8, 63, <https://doi.org/10.3390/geosciences8020063>.

Schlundwein V, Dreutter S, Dorschel B, Kanzow T, 2023 Multibeam bathymetry raw data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS131, PANGAEA, <https://doi.org/10.1594/PANGAEA.953860>.

Schulze Tenberge Y, Konopatzky P, Dreutter S, Dorschel B, Multibeam bathymetry processed data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS135/1, Atlantic Ocean, PANGAEA 2023a, <https://doi.org/10.1594/PANGAEA.961241>.

Schulze Tenberge Y, Konopatzky P, Dreutter S, Dorschel B, Multibeam bathymetry processed data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS135/2, Atlantic Ocean, PANGAEA 2023b, <https://doi.org/10.1594/PANGAEA.961240>.

Schulze Tenberge Y, Konopatzky P, Dreutter S, Dorschel B, Multibeam bathymetry raw data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS135/1, PANGAEA 2023c, <https://doi.org/10.1594/PANGAEA.958676>.

Schulze Tenberge Y, Konopatzky P, Dreutter S, Dorschel B, Multibeam bathymetry raw data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS135/2, PANGAEA 2023d, <https://doi.org/10.1594/PANGAEA.958677>.

Schulze Tenberge Y, Lemire A, Andreas P, Dreutter S, et al., Multibeam bathymetry processed data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS140, Southern Ocean, PANGAEA 2024a, <https://doi.org/10.1594/PANGAEA.967619>.

Schulze Tenberge Y, Lemire A, Andreas P, Dreutter S, et al., Multibeam bathymetry raw data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS140, PANGAEA 2024b, <https://doi.org/10.1594/PANGAEA.966176>.

Schulze Tenberge Y, Schwarzbach P, Dorschel K, Dreutter S, et al., Multibeam bathymetry processed data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS132, Transit, Atlantic Ocean, PANGAEA 2023e, <https://doi.org/10.1594/PANGAEA.954700>.

Schulze Tenberge Y, Schwarzbach P, Dorschel K, Dreutter S, et al., Multibeam bathymetry raw data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS132, PANGAEA 2023f, <https://doi.org/10.1594/PANGAEA.956866>.

Warnke F, Unland E, Höppner L, Dorschel B, et al., Multibeam bathymetry raw data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS137, PANGAEA 2024, <https://doi.org/10.1594/PANGAEA.963721>.

Warnke F, Unland E, Höppner L, Dreutter S, et al., Multibeam bathymetry processed data (Atlas Hydrosweep DS 3 echo sounder entire dataset) of RV POLARSTERN during cruise PS137, Western Gakkel Ridge, Arctic Ocean, PANGAEA 2023, <https://doi.org/10.1594/PANGAEA.963220>.

Wölfl A-C, Snaith H, Amirebrahimi S, Devey CW, et al., Seafloor Mapping – The Challenge of a Truly Global Ocean Bathymetry, *Frontiers in Marine Science* 2019, 6, 283, <https://doi.org/10.3389/fmars.2019.00283>.

PS131

ICE-Jelly: Influence of sea-ice and sub-mesoscale oceanography on jelly distributions and communities

Author

University of Bremen | Bremen, Germany
C. Havermans

Project summary

Gelatinous zooplankton (GZP) or “jellies” are a broad group of taxa, comprised of ctenophores, cnidarians and tunicates. They are largely understudied despite hypotheses of recent increases in biomass throughout the World’s Oceans. This phenomenon, referred to as “ocean jellification”, is likely a result of the complex interplay of climate change, overfishing and other anthropogenic factors. Environmental changes are occurring at an unprecedented pace in the Arctic Ocean, urgently highlighting the need for a large-scale understanding of Arctic marine biodiversity. Pioneering work has shown GZP to be particularly abundant in Arctic waters, including under-ice environments. GZP species are also known to aggregate at hydrographic features because of their affinities to certain water masses. However, little is known about GZP diversity, abundances and community structure in the Arctic in general, and even less at the sub-mesoscale. Hence, the ICE-Jelly project, a secondary user programme carried out during the expedition PS131 to the Arctic in 2022, aimed to investigate GZP diversity and small-scale distribution patterns along a sea-ice gradient and at mesoscale and sub-mesoscale spatial scales. We focused on particular features such as the halocline, fronts and ice regimes in the marginal ice zone (MIZ). To do so, we combined net catches with optical and environmental DNA (eDNA) surveys, optical surveys (with the Underwater Vision Profiler) and environmental data. These integrative studies significantly boosted our understanding of GZP dynamics, as well as metazoan under-ice ecology in general (Murray et al., 2025) and allow us to improve predictions on the future Arctic ecosystem.

ICE-Jelly programme goals

The overarching goal of the ICE-Jelly research programme was to establish a comprehensive baseline knowledge of jelly diversity and distributional patterns and their link to oceanographic patterns and sea ice. We collected species-level GZP data along a sea-ice gradient, from open ocean across the Marginal Ice Zone (MIZ) to the pack ice. We focused also on the sub-mesoscale, by testing for differences in pelagic community structure along particular oceanographic features such as fronts and the halocline (see Figure 1). To do so, we applied integrative jelly surveys, combining depth-stratified net sampling with non-invasive methods including environmental DNA (eDNA) and optical (imaging) surveys with the Underwater Vision Profiler (UVP) and video footage under the ice. These surveys allowed us to study how jelly aggregations, distributions and feeding habits change in different regions and water masses, and from open ocean across the Marginal Ice Zone (MIZ) to the pack ice. These datasets of unprecedented spatial resolution improved our understanding of GZP dynamics, ecology and to improve predictions on future GZP communities.

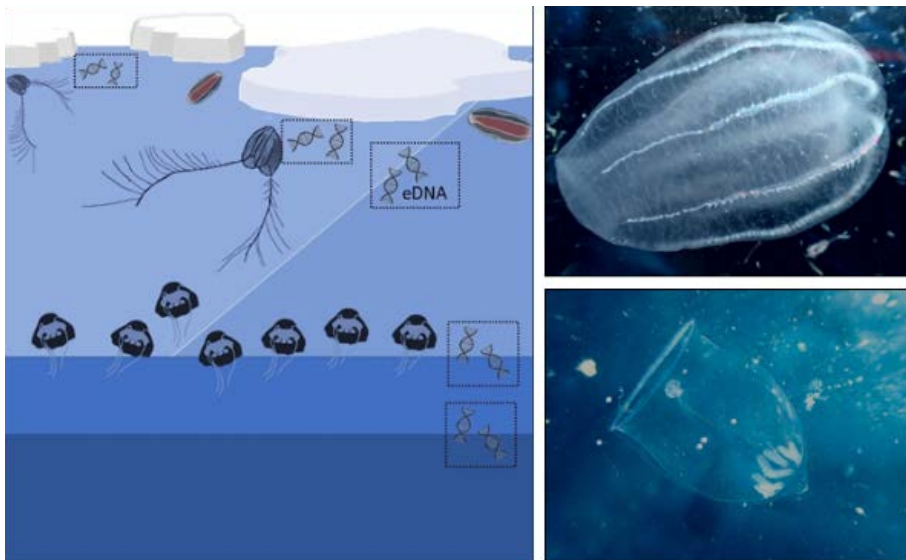


Figure 1: Left: A schematic drawing illustrating the small-scale distributions of GZP we aim to assess with the ICE-Jelly programme. Right: Arctic GZP species known to be abundant under the ice: the ctenophore *Beroë cucumis* and the hydrozoan *Aglantha digitale*.

The objectives of the ICE-Jelly project were to:

- Study species richness, community composition and small-scale distributions of GZP and link these to environmental parameters. Species distributions were assessed vertically and along sea-ice and sub-mesoscale hydrographic

gradients – *using plankton net catches, DNA barcoding, eDNA metabarcoding, UVP surveys, under-ice GoPro™ footage*;

- Obtain and compare GZP abundance data from different sampling methods across different hydrographic and sea-ice gradients – *using plankton net catches, UVP surveys*;
- Elucidate the trophic role of dominant jellies in local Arctic food webs and their reliance on sea-ice associated food sources – *using plankton net catches, biomarker and molecular diet analyses*;
- Identify GZP “bioregions” based on data from the different sampling methods in the various sampling areas of open water, MIZ, and pack ice – *species distribution and community distribution modelling*;
- Compare GZP species composition at the same localities over several years and link this to local hydrography and other environmental parameters – *eDNA time series at several LTER-HAUSGARTEN stations (2019-2022), plankton net catches*.

ICE-Jelly sampling

The working area during PS131 consisted of different target regions: i) the West Spitsbergen Current in Fram Strait, ii) the transition from open waters to the MIZ and the pack ice on the Yermak Plateau, iii) the Aurora Vent field, iv) the East Greenland Shelf and v) Scoresby Sound. In total, 23 pelagic stations and 13 ice stations were comprehensively sampled. Zooplankton were sampled with the Multi-Net at 13 sites, while eDNA samples were collected from CTD casts at 23 pelagic sites, and with a hand Niskin at 11 ice stations. Optical surveys were conducted with the UVP at 58 sites and with the GoPro at all 11 ice stations. We conducted Midi-Multinet (Midi-MN) deployments at three LTER-HAUSGARTEN stations (S3, HG-IV, N4), and sampled water at specific depth intervals from the surface to above the seafloor for eDNA studies from the CTD rosette. To investigate small-scale distributions of GZP and identify potential aggregations of different species according to oceanographic features, sampling was carried out based on mesoscale features detected with the towed oceanographic measurements gear “TopAWI”. These included two transects from open water into the MIZ and the second across an ice tongue feature at the edge of the MIZ. The sampling transects were identified based on TopAWI profiles and according to sea-ice distribution patterns. At these locally identified gradients, we carried out depth-stratified sampling of the shallower layers with Midi-MN deployments where possible, water from the CTDs for eDNA analyses, and UVP surveys. Stations on the East Greenland Shelf and coast were also sampled comprehensively with eDNA, UVP and Midi-MN where possible (depending on ice conditions). One

LTER-HAUSGARTEN station on the slope of the EG shelf (EGVI), two coastal stations in fast-ice near the 79°N glacier and two stations in Scoresby Sound were sampled in this area. To characterize GZP diversity and distribution under the ice, ice stations were conducted on the three focus ice floes at each of the three visits. Additional ice stations were sampled at the Aurora Vent Field and over the Yermak Plateau (24-hour ice station). At all ice stations, water sampling was carried out in through drill holes. Water sampling for eDNA studies was done by deploying a 2.5L Hydrobios Niskin bottle. 6L of water was taken from the under-ice interface and at 5m depth and filtered over 0.2 µm Sterivex filters (2L per filter). We conducted visual surveys in each eDNA ice-hole with a GoPro™ camera, to capture footage of any GZP aggregations under the ice. At three ice-floe stations (North Floe – visit 3, Middle Floe – visit 3 and the 24-hour station), eDNA samples and GoPro surveys were conducted in three holes (50m – 100m apart) across the floe to investigate within-floe variation in eDNA distribution.

We sampled water from the CTD rosette for eDNA analyses at 23 stations across Fram Strait, the MIZ and Greenland and 11 ice stations. We sampled GZP with the Midi-MN at 13 different stations at depths ranging from the surface to 1500m water depth.

ICE-Jelly results so far

The most abundant species encountered during this cruise and at the majority of the sampled stations were the hydrozoan *Aglantha digitale*, the hydrozoan *Sminthea arctica* and the siphonophore *Dimophyes arctica*. Based on our preliminary results, the East Greenland Shelf stations exhibited more species richness than the other stations, including the hydrozoan species *Aeginopsis laurentii* and the scyphozoan genus *Atolla*. More than 300 GZP individuals were collected during this cruise, the majority of which was photographed and frozen or preserved individually. For several species, DNA barcoding has been carried out to validate species identification with molecular barcoding (COI or 18s markers). Results are currently in preparation for publication in the shape of a dataset created in the “The Barcode of Life Data Systems BOLD”.

Regarding the eDNA samples, the under-ice seawater samples from the ice stations were used for a multi-marker metabarcoding dataset that has been analyzed in detail. We studied the nuclear ribosomal 18S rRNA v1-2 gene fragment and the mitochondrial COI “Leray-XT” gene fragment to investigate the eukaryotic diversity of the upper water column under the ice, from seawater samples collected directly beneath the sea ice and at a depth of 5 m, sourced from ice floes representing different ice regimes. These samples were sequenced on an Illumina NovaSeq platform. The dataset was investigated from an interdisciplinary perspective: we explored the abiotic factors influencing under-ice diversity by

comparing the genetic datasets with satellite-derived environmental data as well as associated in-situ hydrographic measurements (published in Murray et al. 2025). Our analysis identified a range of sympagic and pelagic metazoan taxa, as well as primary producers, several of which known for the region. The most striking finding was the substantial amount of uncharacterized diversity, i. e. DNA reads that could not be assigned to a taxon based on DNA reference libraries. Alpha diversity was higher immediately below the ice compared to the 5m layer beneath it. Community composition and species richness were influenced by the distance to the ice edge, the meltwater stratification in the upper layer and the sea ice concentration, showing the the communities in the Marginal Ice Zone are unique and therefore susceptible to climate-induced changes in ice properties (Murray et al., 2025).

So far, DNA has been isolated for the majority of the eDNA samples and specific regional studies, e. g. on the metazoan diversity at the Aurora Vent site, are currently ongoing.

References

Murray A, Ramondenc S, Reifenberg SF, Jucker M, Neudert M, McPherson R, von Appen W-J & Havermans C, Eukaryotic biodiversity of sub-ice water in the marginal ice zone of the European Arctic: A multi-marker eDNA metabarcoding survey, *Science of the Total Environment* 2025, 968, 178840, doi: 10.1016/j.scitotenv.2025.178840.

PS131

WALSEMA during PS131: Water vapor, cloud liquid water and surface emissivity

Authors

Institute of Environmental Physics, University of Bremen | Bremen, Germany

J. Rückert, G. Spreen

Institute for Geophysics and Meteorology, University of Cologne | Cologne, Germany

K. Ebell, M. Mech, A. Walbröl

Measurement setup

The WALSEMA “Water Vapour, Cloud Liquid Water, and Surface Emissivity over the Arctic Marginal Ice Zone in Summer” project was a secondary user project during the ATWAICE (PS131) campaign from June to August 2022. Two microwave radiometers were installed on Polarstern’s Peildeck: MiRAC-P (Microwave Radiometer for Arctic Clouds – Passive) (Mech et al., 2019) observing at high-frequencies (six channels around 183.31 GHz and two window channels centered at 243 and 340 GHz) and HATPRO (Humidity and Temperature Profiler), with seven channels each at K-band and V-band (Rose et al., 2005). In addition, a visual and an infrared (IR) camera facing the surface were installed next to the radiometers. Rotatable mirrors were attached to the radiometer stand to allow measurements towards the atmosphere and the surface. A sky camera (visual and IR) was complementing the microwave measurements. The setup is displayed in Figure 1.

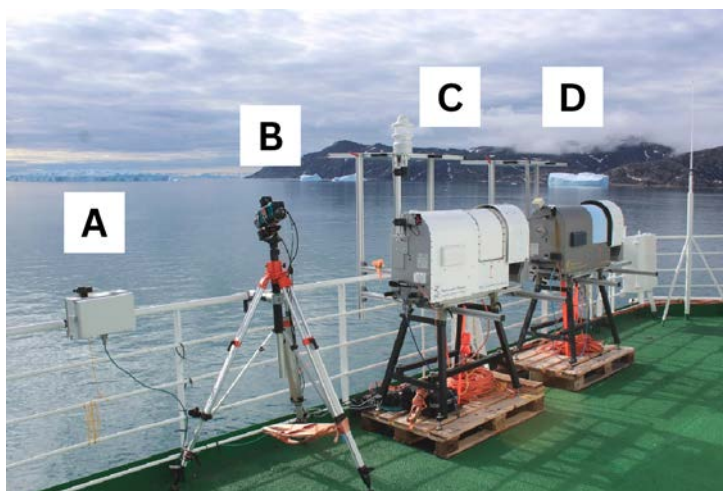


Figure 1: WALSEMA measurement setup during PS131 with (A) Sky camera, (B) IR surface camera with VIS surface camera on top, (C) MiRAC-P, and (D) HATPRO.

Atmospheric observations: water vapor and cloud liquid water

Most of the time the radiometers pointed in zenith direction. From these observations vertical profiles of temperature and humidity, as well as liquid water path (LWP) and integrated water vapor (IWV) were derived (Walbröl et al., 2022). Figure 2 shows the errors of the retrieved IWV as well as temperature and humidity profiles with respect to the radiosondes launched during ATWAICE. The excellent agreement of the IWV with a root mean squared error (RMSE) of 0.46 kg m^{-2} and biases of only 0.15 kg m^{-2} demonstrates the high quality of the data. For the temperature profiles, we merged zenith and boundary layer scan observations to improve the vertical resolution in the boundary layer. The comparison to the radiosondes shows relatively small errors of 1–2 K in the lower troposphere despite the presence of strong temperature inversions, which are difficult to resolve with passive microwave observations. Temperature biases are also mainly between -1 and +1 K. The retrieved absolute humidity (ρ_v) profiles have relative RMSE (normalized by the radiosonde data) of about 20 % in the lower and up to 50 % in the upper troposphere.

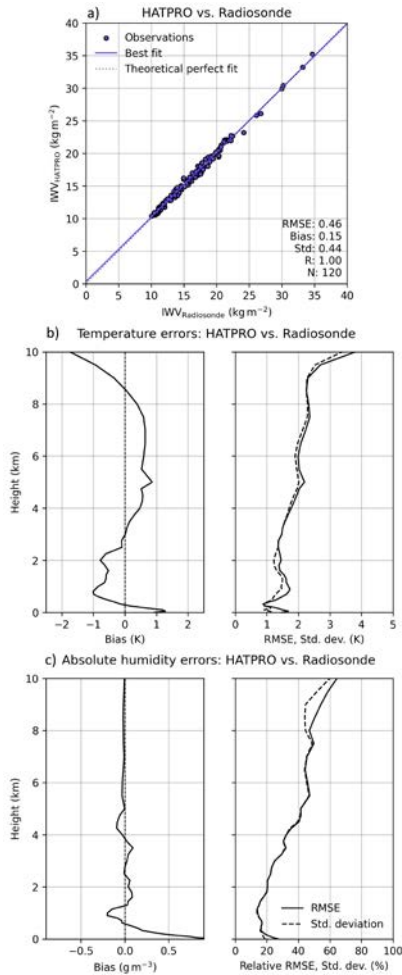


Figure 2: Comparison between meteorological observations (integrated water vapor, temperature profiles and humidity profiles) from radiosondes and microwave from radiometer data. In a) we show a scatterplot of integrated water vapor (IWV) from the radiosonde data vs the collocated IWV derived from the radiometer data. Differences in temperature profile (b) and absolute humidity profile (c) are shown as bias and root mean square error (RSME) in the other two panels.

The most notable event recorded with these atmospheric measurements is a series of two warm and moist air intrusion that occurred from 15–17 July and 17–19 July. Significant and untypically high moisture (IWV of 35 kg m^{-2}) and temperatures up to 18°C at 650 m altitude were recorded at Polarstern, which was residing on the lee side of Svalbard at that time (see Figure 3). The LWP, derived with an uncertainty of approximately 20 g m^{-2} , shows the highly variable cloud conditions encountered during PS131. During the warm air intrusions, the LWP varied between 0 and 350 g m^{-2} .

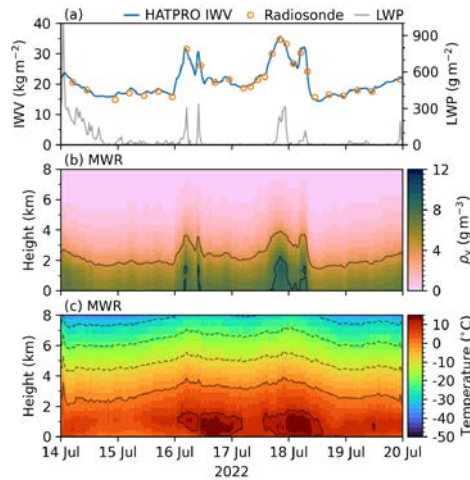


Figure 3: Measurements of integrated water vapor (IWV) and liquid water path (LWP) (a), humidity (b) and temperature profiles (c) from the microwave radiometers. In addition, IWV from radiosondes is shown in a). Shown is the time period around the two warm air intrusions.

Surface observations: Microwave emissivity

In addition to the atmospheric observations, the mirror construction enabled us to point at the surface. Since the cruise was conducted in the melting season, the physical temperatures of the encountered ocean, (bare) ice, and melt pond surfaces were similar and thus changes in the measured microwave brightness temperatures can be mainly attributed to changes in emissivity. The surface observations were done on a regular basis each hour at a viewing angle of 53° for 15 minutes. Note that the measured brightness temperatures have frequency-dependent polarizations. The surface was also scanned at various zenith angles five times during the cruise when the mirror was rotated manually. However, due to the heterogeneous ice surface (melt ponds, leads, bare ice), which changes with incidence angle, the angle-dependence analysis is not conclusive.

The measured microwave brightness temperatures at 53° show distinct signatures for different surface types in the marginal ice zone at the low frequencies between 22 and 31 GHz, where it can be assumed that the atmosphere does not dominate the signal.

Brightness temperatures are around 160 K for open water and around 260 K for ice observations. At 51.26 and 52.28 GHz a contrast between sea ice and open water is observed as well. No distinction between ocean and sea ice was identified for the other frequencies in the 58 GHz oxygen absorption complex. Here, the atmospheric contributions dominate the signal and the signals correspond to the air temperatures. Similarly, no distinct surface signal could be identified

at the frequencies along the 183 GHz water vapor line where the atmospheric contributions caused by water vapor are dominating and the signals correspond to integrated water vapor values. At 243 GHz, the atmospheric moisture has a stronger influence than between 22 and 31 GHz but is not dominating the signal and the surface again is the main contributor. But because of the stronger moisture influence, the ice and ocean have less distinct emission signatures than at frequencies between 22 and 31 GHz.

Using the collocated skin temperatures derived from the infrared camera observations and the down-welling atmospheric contributions derived from the zenith observations, microwave emissivities for all measured frequencies and (pseudo-)polarizations were calculated. One example for 22.24 GHz, where the distinction between open ocean and sea ice is evident, is shown in Figure 3. Here, microwave measurements were collocated with the visual images and it was found, that high emissivities correspond to sea ice (high red-blue (R-B) ratio in the visual camera), while low emissivities correspond to open water (low R-B ratio). Emissivities at 22-31 GHz (predominantly vertically-polarized) between 0.51 ± 0.01 and 0.55 ± 0.01 for open ocean and around 0.95 ± 0.02 for sea ice were derived. At 243 GHz (predominantly horizontally-polarized) the distinction is less pronounced: ice surfaces exhibit a large variability with values around 0.67 ± 0.04 and around 0.83 ± 0.04 . Ocean emissivities at this frequency are around 0.78 ± 0.01 . The results shown can improve the characterization of surface emissions in satellite retrieval algorithms. More details on the surface microwave emissivity observations can be found in Rückert et al., 2025.

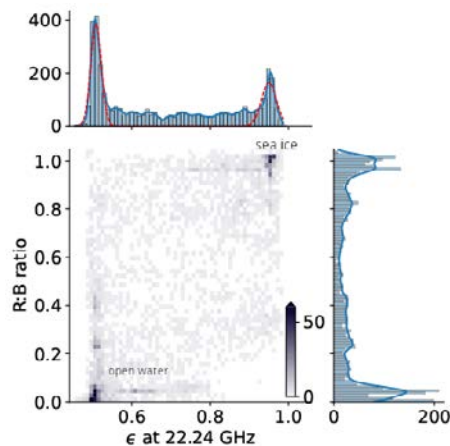


Figure 4: Emissivity ϵ at 22.24 GHz co-located with the ratio of red (R) to blue (B) from the RGB images of the visual camera. Shown are bivariate and marginal histograms with kernel density estimates (blue line).

References

Mech M, Kliesch LL, Anhäuser A, Rose T, Kollias P & Crewell S. Microwave radar/radiometer for Arctic clouds (MiRAC): First insights from the ACLOUD campaign, *Atmospheric Measurement Techniques* 2019, 12(9), 5019–5037, doi: 10.5194/amt-12-5019-2019.

Rose T, Crewell S, Löhnert U and Simmer CA. Network suitable microwave radiometer for operational monitoring of the cloudy atmosphere, *Atmospheric Research* 2005, 75(3), 183–200, doi: 10.1016/j.atmosres.2004.12.005.

Rückert JE, Walbröl A, Risse N, Krobot P, Haseneder-Lind R, Mech M, Ebell K & Spreen G, Microwave sea ice and ocean brightness temperature and emissivity between 22 and 243 GHz from ship-based radiometers, *Annals of Glaciology* 2025, 66:e8, 10.1017/aog.2025.1.

Walbröl A, Crewell S, Engelmann R, Orlandi E, Griesche H, Radenz M, Hofer J, Althausen D, Maturilli M & Ebell K, Atmospheric temperature, water vapour and liquid water path from two microwave radiometers during MOSAiC, *Scientific Data* 2022, 9, 534, doi: 10.1038/s41597-022-01504-1.

Walbröl A, Griesche HJ, Mech M, Crewell S & Ebell K, Combining low- and high-frequency microwave radiometer measurements from the MOSAiC expedition for enhanced water vapour products, *Atmospheric Chemistry and Physics* 2024, 17(20), 6223–6245, doi: 10.5194/amt-17-6223-2024.

PS133/2

Natural organic matter coatings on iron oxides shape microbe–mineral–organic carbon interactions in marine sediments

Authors

MARUM – Center for Marine Environmental Sciences, University of Bremen | Bremen, Germany

Y. Chen, H. Taubner, V. Heuer, J. Altun, R. van Kaam, W. Bach, S. Kasten, M. Zabel, K.-U. Hinrichs, M. W. Friedrich

Microbial Ecophysiology Group, Faculty of Biology/Chemistry, University of Bremen | Bremen, Germany

Y. Chen, A. Helms, L. C. Wunder, M. W. Friedrich

Faculty of Geosciences, University of Bremen | Bremen, Germany

H. Taubner, V. Heuer, J. Altun, W. Bach, S. Kasten, K.-U. Hinrichs

Solid State Chemical Crystallography, Faculty of Biology/Chemistry, University of Bremen | Bremen, Germany

L. Robben

Data Science Center, University of Bremen | Bremen, Germany

L. Robben

MAPEX – Center for Materials and Processes, University of Bremen | Bremen, Germany

L. Robben

Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany

S. Kasten

Iron oxides associate with organic matter in various environments, thereby protecting organic matter from microbial degradation¹. However, research into how this protection may be influenced by the microbially-mediated processes in anoxic marine sediments remains limited². Here, we studied the interaction between synthesized ferrihydrite (Feh) and ¹³C-labeled acetate in incubations with surface sediments from Cumberland Bay (South Georgia, Sub-Antarctic), which

were collected during RV POLARSTERN cruise PS133-2. Meanwhile, a natural organic matter (NOM) coating was put on the Feh surface to study its effect on the interaction between Feh, acetate and microbes. The NOM was extracted from the surface sediments using MilliQ water, and then adsorbed onto Feh surface, achieving a final organic carbon (OC) loading of 0.21 mol OC/mol Fe (Figure 1). During the incubation, we found that adding freshly synthesized Feh promoted acetate protection by 50% in the absence of microbially mediated iron reduction (Figure 2). In contrast, adding Feh precoated with NOM promoted acetate protection by 102% (Figure 2). When microbially mediated iron reduction was active, we observed significant differences. While only a limited amount of Feh-protected acetate was remobilized from fresh Feh, 76% of the acetate was remobilized from precoated Feh (Figure 2). These findings suggest that organic matter coatings initially strengthen the protection of small organic molecules by iron oxides but simultaneously increase the susceptibility of these associations to microbially mediated iron reduction, which could remobilize the iron-bound organic matter. This is likely due to the larger surface area resulting from smaller aggregate sizes, as demonstrated by SEM micrographs (Figure 3). Thus, natural organic matter coatings fundamentally alter microbe-mineral-organic carbon interactions, and consequently the fate of iron-bound organic matter. Our findings provide new insights into the role of iron oxides in carbon cycling in the marine environment.

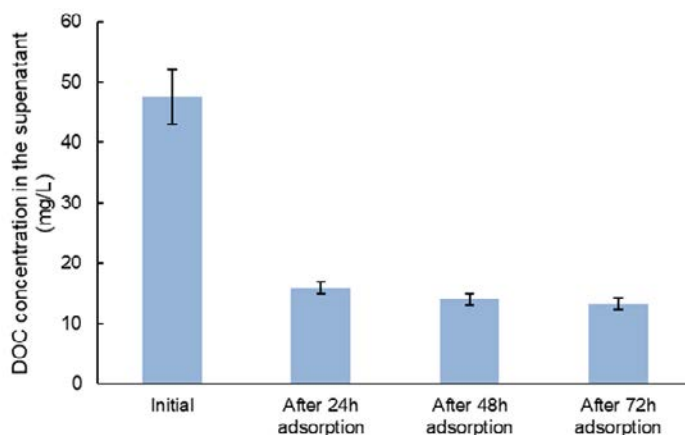


Figure 1: Decreasing DOC concentration in the supernatant during the adsorption experiment of the NOM solution and Feh indicated adsorption of NOM on Feh.

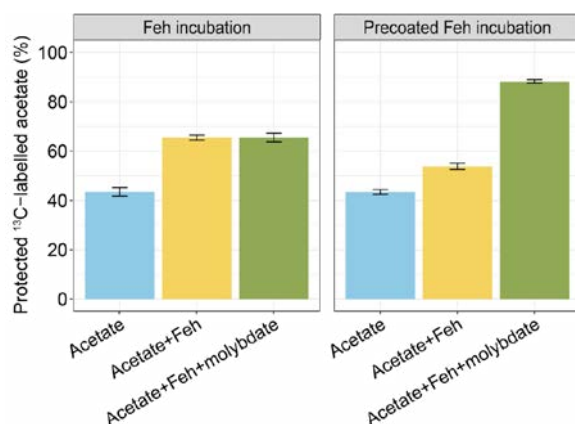


Figure 2: The percentage of ^{13}C -labelled acetate being protected by solid phases, i. e., sediment particles and Feh, in different treatments after seven days of incubation. The treatment “Acetate” studied the acetate degradation without Feh protection (blue bars). The treatment “Acetate+Feh” studied the acetate degradation with partial Feh protection, where microbially mediated iron reduction could potentially remobilize Feh-protected acetate (yellow bars). The treatment “Acetate+Feh+molybdate” studied the acetate degradation with full Feh protection, where microbially mediated iron reduction was stopped by adding molybdate (green bars).

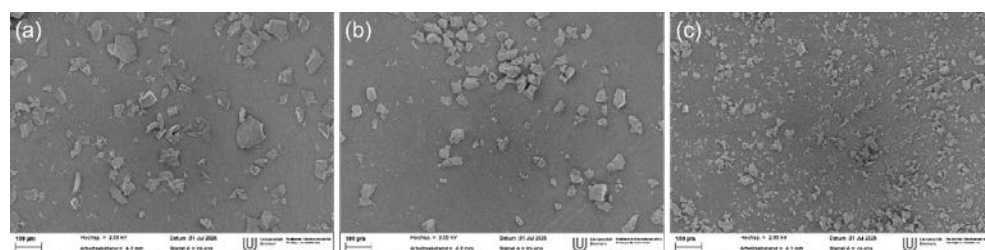


Figure 3: SEM micrographs of Feh (a), Feh in acetate (b), and precoated Feh in acetate (c) show smaller aggregates of precoated Feh.

References

Lalonde K, Mucci A, Ouellet A & Gélinas Y, Preservation of organic matter in sediments promoted by iron, *Nature* 2012, 483, 198-200, <https://doi.org/10.1038/nature10855>.

Chen Y, Dong L, Sui W, Niu M, et al., Cycling and persistence of iron-bound organic carbon in subseafloor sediments, *Nat. Commun* 2024. 15, 6370, <https://doi.org/10.1038/s41467-024-50578-5>.

PS133/2

Iron Isotope Constraints on Iron Sources from South Georgia to the Southern Ocean

Authors

Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany

B. Ebner, S. Henkel, J. Stimpfle, S. Trimborn, F. Koch, R. Mole, C. Völkner, I. Stimac, D. Müller, M. Köster, L. Kattein, W. Geibert, S. Kasten

University of Bremen | Bremen, Germany

B. Ebner, J. Stimpfle, R. Mole, D. Müller, L. Kattein, S. Kasten

MARUM-Center for Marine Environmental Sciences | Bremen, Germany

S. Henkel, S. Kasten

Royal Netherlands Institute for Sea Research | Texel, Netherlands

P. Kraal

Institute of Geology and Mineralogy, University of Cologne | Cologne, Germany

M. Staubwasser

GEOMAR-Helmholtz Centre for Ocean Research | Kiel, Germany

K. Laufer-Meiser

Université de Toulouse, LEGOS (CNES/CNRS/IRD/UT) | Toulouse, France

F. Lacan, C. Pradoux

Abstract

Iron is an essential nutrient that algae need to grow, yet large regions of the Southern Ocean remain iron-limited, with phytoplankton growth strongly dependent on the availability of iron. Coastal sediments surrounding sub-polar islands have been proposed as significant benthic sources of dissolved iron capable of sustaining downstream phytoplankton blooms. These prominent phytoplankton blooms have been observed in response to Fe fertilization processes along the shelf and continental regions of the Antarctic Peninsula as

well as in the downstream areas of subpolar islands such as the Crozet Islands, the Kerguelen Plateau and South Georgia. Benthic iron (Fe) fluxes from coastal sediments of our study area South Georgia potentially fuel these phytoplankton blooms occurring in the Georgia Basin northwest of the island. Increasing benthic Fe fluxes are expected due to glacier retreat, deep thaw of soils and hence elevated rates of weathering, but estimates of current Fe fluxes by benthic release range over three orders of magnitude. Due to the low temporal and spatial resolution of available data on benthic Fe fluxes, the quantification of global Fe fluxes from shelf sediments is currently poorly constrained. However, resolving the dynamics of both the sediment and water column requires particular attention to the sediment-water interface, as this critical boundary layer governs the release and transformation of iron into the open ocean. Here, we focus on identifying the specific Fe sources and assess in which form and by which processes Fe is laterally transported towards the open ocean.

As part of the RV POLARSTERN cruise PS133-2 “Island Impact” (also officially approved as GEOTRACES process study) in austral summer 2022 the aim was to quantify the magnitude and main drivers of these benthic Fe fluxes. We combined solid-phase and pore-water geochemical data, including the pore-water iron isotopic signature ($\delta^{56}\text{Fe}_{\text{aq}}$), to assess the magnitude and drivers of benthic Fe fluxes in sub-Antarctic fjord sediments around South Georgia in two model areas namely Cumberland Bay Fjord and King Haakon Bay. However, a thorough understanding of early diagenetic Fe cycling, determined by the depositional environment, is essential for (1) identifying the primary drivers on benthic Fe fluxes and the pore-water $\delta^{56}\text{Fe}_{\text{aq}}$ signature in the uppermost centimeters of the sediment and (2) to assess, whether or not the pore-water $\delta^{56}\text{Fe}_{\text{aq}}$ value represents a reliable proxy for the dFe flux into the overlying water column. Furthermore, we also collected seawater samples using a new trace-metal clean Rosette CTD system to determine dissolved Fe concentrations and the seawater $\delta^{56}\text{Fe}_{\text{aq}}$ composition. At shallow stations we sampled the water column with handheld GoFlo water bottles from a zodiac.

Our results reveal a strong positive correlation between the magnitude of diffusive benthic Fe fluxes and the total organic carbon accumulation rate (MARTOC), which controls the redox zonation of the shallow sediments and hence the range of the pore-water $\delta^{56}\text{Fe}_{\text{aq}}$ values. Sites with low diffusive Fe fluxes show a broad range of pore-water $\delta^{56}\text{Fe}_{\text{aq}}$ values close to the sediment-water interface ($-3.94 \pm 0.14\text{‰}$ to $-0.98 \pm 0.11\text{‰}$), while sites with high benthic Fe fluxes exhibit a slightly narrower range ($-3.14 \pm 0.02\text{‰}$ and $-1.64 \pm 0.06\text{‰}$). The broader range for sites characterized by low Fe fluxes is discussed in terms of a variety of isotope fractionation processes and their respective mass balance of dissolved Fe ($\text{Fe(II)}_{\text{aq}}$) and solid-phase Fe ($\text{Fe(III)}_{\text{solid}}$) distribution, including 1) low rates of microbial Fe reduction, (2) reaction of $\text{Fe(II)}_{\text{aq}}$ with hydrogen sulfide and precipitation of Fe sulfides and (3) re-oxidation of $\text{Fe(II)}_{\text{aq}}$ within a comparatively

broad oxic and nitrate-containing zone. The comparatively narrow range of pore-water $\delta^{56}\text{Fe}_{\text{aq}}$ in the oxic zone at sites of high Fe fluxes, however, still qualifies $\delta^{56}\text{Fe}_{\text{aq}}$ as a proxy for benthic Fe sources in areas where those are substantial. However, the application of the $\delta^{56}\text{Fe}_{\text{aq}}$ in the water column as a robust indicator of a significant benthic supply of Fe_{aq} into the bottom water that is distinct from other oceanic Fe sources remains challenging. We strongly recommend to take early diagenetic processes in surface sediments into account when using the $\delta^{56}\text{Fe}_{\text{aq}}$ of the water column as a benthic signal, especially in environments with inhomogeneous depositional conditions. Within the water column, dissolved Fe concentrations were consistently higher at King Haakon Bay Fjord compared to Cumberland Bay Fjord. Seawater $\delta^{56}\text{Fe}_{\text{aq}}$ signatures were generally light in both fjords, as glacial margin systems appear to impart a significantly light composition and high dissolved Fe concentrations into coastal waters. However, $\delta^{56}\text{Fe}_{\text{aq}}$ endmembers for different types of sediments, environmental conditions and biogeochemical processes are not yet well enough constrained. Integrating pore-water, solid-phase, and seawater data provides a coherent framework of the dominant Fe sources, transport mechanisms, and transformation processes linking South Georgia's terrestrial and coastal sediments to Fe supply in the adjacent Southern Ocean.

References

Ebner B, Henkel S, Kraal P, Müller D, Köster M, Staubwasser M, Laufer-Meiser K, Kattein L, Geibert W & Kasten S, Drivers of Benthic Iron Fluxes and the Pore-water Iron Isotopic Signature in Sub-Antarctic Surface Fjord Sediments, 2025 (in review), Global Biogeochemical Cycles.

PS133/2

A Long Shadow of Whaling: Lasting Biogeochemical Legacy in Sediments Near Grytviken, South Georgia

Authors

GEOMAR-Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

K. Laufer-Meiser, K. Wallmann, M. Perner

University of Bristol | Bristol, United Kingdom

C. Bryce

Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany

S. Kasten

Faculty of Geosciences, University of Bremen | Bremen, Germany

S. Kasten

MARUM – Center for Marine Environmental Sciences, University of Bremen | Bremen, Germany

S. Kasten

Grytviken, located on the island of South Georgia within the Cumberland Bay fjord, has a unique and troubled history as one of the most important whaling stations in the Southern Ocean. Established in 1904 by the Norwegian whaler Carl Anton Larsen, it became the first shore-based station in Antarctic waters and quickly developed into the hub of a rapidly expanding industry. Over the following decades, industrial-scale whaling transformed South Georgia into the epicenter of global whale processing. At Grytviken alone, more than 50,000 whales were landed and processed between 1904 and the mid-1960s, providing oil and meat to European and global markets. However, this intensive exploitation came at the cost of massive ecological disruption, driving whale populations to collapse. As catches declined, operations became increasingly unsustainable, and the station was eventually abandoned in 1966. The processing of thousands of whales each season released enormous quantities of blood, oil, and organic residues directly into the fjord, enriching the water and sediments with carbon, nitrogen,

and sulfur compounds. While the direct impact on the fjord ecosystem was not studied at that time, and by now the visible remains of the station have become rusty, the question remains whether such organic enrichment could have left a lasting biogeochemical footprint in the seabed. By the time of RV POLARSTERN cruise PS133-2 “Island Impact” in November and December 2022, more than fifty-five years had passed since whaling ended. We applied geochemical and microbiological methods to study if the sediments surrounding this site still bear the imprint of such intense human activity, or if have they reverted to a more natural state.

Our observations provide a striking answer. Sediments adjacent to Grytviken are visually and geochemically distinct from other South Georgia sites and from high-latitude fjords more broadly. The upper layers are characterized by a thin orange-brown surface horizon underlain by pitch-black sediments, a stratification very different from all other sites that were visited during PS 133-2, and other polar fjord sediments in general, that immediately signals unusual redox conditions. Geochemical analyses reveal exceptionally high sulfate reduction rates (SRR), among the highest measured in sub-Antarctic marine sediments. SRR reached $400 \text{ nmol cm}^{-3} \text{ d}^{-1}$ directly at the sediment surface, about 10x higher compared to maximum rates measured at other sites in the same fjord. These rates, together with porewater chemistry and solid-phase Fe extractions, demonstrate a dynamic and tightly coupled iron-sulfur cycle. Such elevated SRR are rarely observed outside of heavily eutrophic coastal zones. The black coloration and sharp Fe redox gradients indicate rapid cycling between reduced and oxidized sulfur and iron phases, possibly sustained by buried organic matter deposited decades ago.

The persistence of these features more than five decades after the cessation of whaling highlights the extraordinary longevity of anthropogenic legacies in sedimentary systems. The Grytviken site thus provides a natural laboratory for understanding how intense anthropogenic inputs can alter sediment biogeochemistry, redox stratification, and microbial ecology on long timescales. During the whaling period, vast amounts of organic matter and processing waste were discharged directly into the surrounding embayment. This still stimulates microbial activity and drives the extraordinarily high SRR and creates microbial communities adapted to these conditions. Remarkably, these imprints have not been erased by half a century of natural sedimentation and post-depositional mixing. Instead, they remain clearly visible in both the physical appearance and the metabolic functioning of the sediment column.

Our findings from Grytviken therefore provide a rare case study of “sedimentary memory” – the ability of benthic environments to retain signatures of past human disturbance on multi-decadal timescales. By linking the industrial history of South Georgia to modern-day sediment geochemistry, our study bridges ecological, historical, and geobiological perspectives. Grytviken today is best known as a

heritage site commemorating the whaling era. Yet beneath the waters offshore, the sediments continue to tell their own story of disturbance, resilience, and long-lived biogeochemical transformation. This makes Grytviken not only a site of historical and cultural memory, but also a natural laboratory for investigating the lasting imprint of human activities on marine sediments. As human activities increasingly extend into remote oceanic regions, understanding such long-term sedimentary legacies becomes essential for predicting the resilience of marine biogeochemical cycles. Grytviken exemplifies how past exploitation can continue to shape benthic functioning long after surface ecosystems appear recovered, reminding us that the seabed preserves a deeper and slower record of human impact.

PS133/2

Trophodynamics and Functional Traits in Macrofauna of SG Methane Seeps

Authors

British Antarctic Survey | Cambridge, United Kingdom

M. Anderson, K. Linse

Newcastle University | Newcastle upon Tyne, United Kingdom

W.D.K. Reid, B.D. Wigham

Alfred Wegener Institute | Bremerhaven, Germany

S. Kasten, I. Dohrmann

National Environmental Isotope Facility | Glasgow, United Kingdom

J. Newton

Bangor University | Bangor, United Kingdom

P. Hollyman

Approximately one-quarter of global marine methane, a potent greenhouse gas, is estimated to be stored within Southern Ocean sediments. In recent years, first records of methane seepages from the seafloor and raised methane concentrations in the overlying water column have been reported from sub-Antarctic islands and the Antarctic shelf. Ongoing climate-driven ocean warming and ice shelf retreat threaten the stability of sedimentary gas hydrates, potentially triggering methane degassing and the development of seep systems. These seeps may originate from multiple sources, but hydrate destabilisation likely contributes to the formation and persistence of some active systems. The ecological impact on the diverse sub-Antarctic and Antarctic benthic communities remain uncertain.

Evidence of methane seepage has come from a number of sources including the detection of raised methane in sediments at the eastern Antarctic Peninsula, gas flares on the Kerguelen Plateau, gas hydrate in the South Georgia shelf and methane seepage including bacterial mats in nearshore, shallow waters of the Ross Sea. However, to date no living chemosynthetic mega- or macrofauna, generally associated with deep-sea methane seepage have been reported from

the SO seepage sites. In our study, we investigated macrobenthic fauna on the shelf of South Georgia. The benthic fauna of South Georgia is known as highly diverse (Figure 1) and marked by a cumulative dominance of endemic and range-edge species, as well as by a high number of recorded rare species.

During PS133-2 we were able to work closely with the marine sedimentologists, microbiologists and geochemists on the methane influenced habitat on the shelf of South Georgia, especially in the Cumberland Bay Fjord, the King Haakon Bay and their associated troughs. Our main sampling device was the OKTOPUS Ltd multicorer (MUC) and we collected in total 43 MUC core tubes for macrofauna analyses from 8 locations. These samples complemented the MUC samples collected for macrobenthos analyses during the expedition M134. Our data presented here investigate macrobenthic assemblages at active methane seeps on South Georgia's continental shelf, examining patterns in species richness, abundance, and the environmental variables shaping community composition. The macrobenthic assemblages of seven shelf troughs were surveyed during the expeditions with M134 on RV Meteor in 2017 (Anderson et al., 2025) and PS133-2 on RV Polarstern in 2022. In total, taxonomic identifications of macrobenthic invertebrates recorded 103 morphospecies across 23 stations. Richness ranged from 6–51 morphospecies and abundances varied from 3,303–30,326 ind. m⁻². Higher diversity occurred at sites with elevated methane and sulfate fluxes and hydrogen sulfide at depth, while elevated surface sulfide and dominant iron-reduction processes corresponded with lower richness and abundance. Stable isotope ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{34}\text{S}$) and functional trait analyses of fauna were used to assess whether methane-derived carbon enters the benthic food webs, and how seep presence alters trophic pathways and benthic ecosystem functioning. Assemblages lacked megafaunal chemosymbiotic taxa and were dominated by annelids and arthropods, with reduced molluscan and echinoderm representation. Seep habitats associated with near-surface hydrates supported lower biodiversity and fewer calcifying taxa, indicating potential risks to Antarctic benthic biodiversity under future seep expansion.

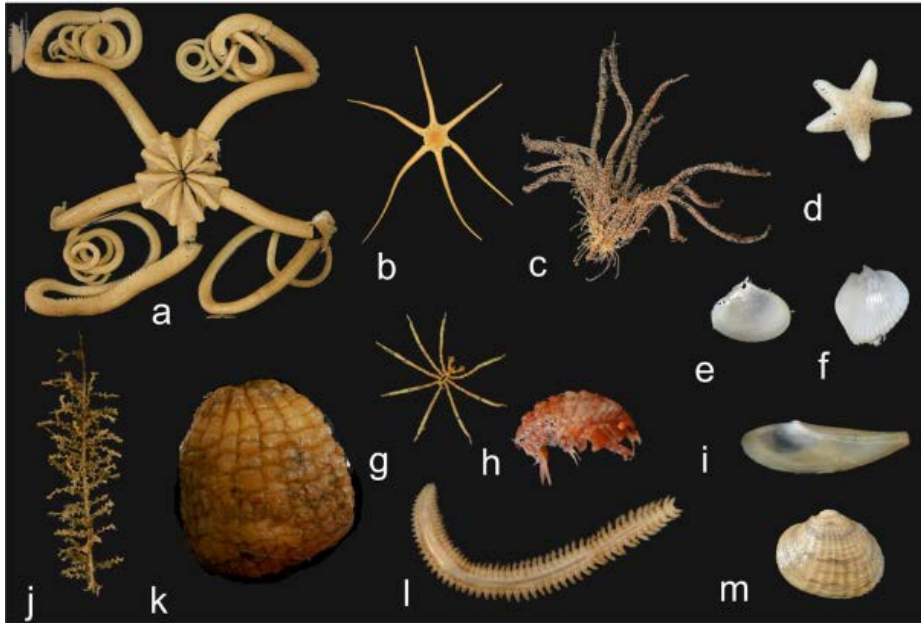


Figure 1: Examples of benthic macro- and megafaunal invertebrates collected during PS133-2: a) *Austrotoma agassizi*; b) ophiuroid; c) *Promatocrinus* sp.; d) asteroid; e) *Ptychocardia vanhoeffeni*; f) *Thracia meridionalis*; g) pycnogonid; h) *Epimeria* cf. *georgiana*; i) *Poroleda longicaudata*; j) primnoid soft coral; k) *Hormathia* sp.; l) nephtyid polychaete; m) *Cyclocardia astartoides*. (photos © Isabella Wilkie).

References

Anderson MPBC, Reid WDK, Bohrmann G, Dohrmann I, et al., The abundance, diversity, and assemblage structure of the macrobenthos at the South Georgia shelf methane seeps. *Frontiers in Marine Science* 2025, 12, 1589660, doi: 10.3389/fmars.2025.1589660.

PS133/2

Contrasting bioavailability of iron in glacial vs. groundwater to Antarctic phytoplankton: Linking iron uptake to geochemistry (PS133-2)

Authors

Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany

J. Stimpfle, F. Koch, B. Ebner, C. Voelkner, S. Trimborn, S. Henkel, S. Kasten

University of Bremen | Bremen, Germany

J. Stimpfle, B. Ebner, S. Kasten

MARUM-Centre for Marine Environmental Science | Bremen, Germany

S. Henkel, S. Kasten

GEOMAR-Helmholtz Centre for Ocean Research | Kiel, Germany

R. Zitoun, C.F. Sukekava, S.G. Sander

Institute for Marine and Antarctic Studies, University of Tasmania | Hobart, Australia

R. Zitoun

Christian Albrechts University | Kiel, Germany

S.G. Sander

University of Washington | Washington, USA

R.M. Bundy, A. Ruacho

Primary production in the Southern Ocean (SO) is constrained by the availability of iron (Fe), resulting in high concentrations of unutilized macronutrients in seawater, making the SO a High-Nutrient Low-Chlorophyll (HNLC) region. Exceptions are observed in the vicinity of islands, where primary production flourishes, sustaining a variety of wildlife and substantially contributing to increased sequestration of atmospheric CO₂, an effect commonly referred to as the Island Mass Effect. Still, little is known about the Fe sources that fuel the high productivity around

South Georgia, which has been estimated to be 10 times higher compared to the surrounding Weddell Sea ($\sim 200 \text{ g C m}^{-2} \text{ yr}^{-1}$ vs. $\sim 20 \text{ g C m}^{-2} \text{ yr}^{-1}$). Observational and modelling studies suggest that sources fueling the blooms off South Georgia originate close to the island's shore, however, Fe supply mechanisms and bioavailability of Fe to phytoplankton remain poorly resolved. Studies estimating Fe fluxes commonly measure certain size classes of dissolved Fe (dFe ($< 0.2 \mu\text{m}$): soluble Fe ($< 0.02 \mu\text{m}$) and colloidal Fe ($0.02\text{--}0.2 \mu\text{m}$)) and assume them to be fully or partially bioavailable. However, these simplifications do not appropriately represent the complex interplay between chemical and physical speciation, such as the complexation with organic ligands and size fractionation that together govern Fe bioavailability. In this study, additional to determination of Fe chemical speciation and assessment of weathering processes, ^{55}Fe uptake by a natural phytoplankton community was quantified.

Accordingly, we sampled different nearshore sources of Fe to assess the bioavailability of Fe to phytoplankton: Groundwater from a subaerial seepage, featuring reddish precipitates; water from proglacial meltwater streams, producing turbid plumes in the fjord, as seen on satellite images and water from the estuary, in the mixing zone where the glacial meltwater stream enters the fjord. Sampling took place in King Haakon Bay on the south-western side of the island and in Cumberland Bay on the north-eastern side. In the framework of the GEOTRACES process study Island Impact (38), we conducted short-term ^{55}Fe uptake experiments with a natural, Fe limited phytoplankton community on board the research vessel Polarstern. Water sampled from a low and a high chlorophyll site was filtered ($0.2 \mu\text{m}$; hereafter referred to as low chl water (LCW) and high chl water (HCW) and enriched with the above-mentioned nearshore Fe sources. The pre-concentrated natural, diatom-dominated phytoplankton community was then added to each treatment and the bioavailability of each source was determined by measuring ^{55}Fe uptake in triplicates after 24h. The uptake experiment also included a treatment with FeCl_3 and unamended bottles (LCW and HCW without source addition) for comparison.

Our study shows that the bioavailability of natural Fe sources from South Georgia was primarily dependent on in-situ biogeochemical interactions in seawater. To differentiate between biological and non-biological removal of Fe, bottles of the LCW and HCW (without Fe addition) were split into biotic (addition of pre-concentrated phytoplankton) and abiotic ones (without addition of phytoplankton). As expected, no Fe uptake occurred in the abiotic LCW due to the absence of phytoplankton cells. Surprisingly, ^{55}Fe was retained on the filters in the abiotic HCW. In fact, the amount of ^{55}Fe in the abiotic HCW was similar to that in the biotic HCW, suggesting an effect driven by chemistry and not by biology. This observation is indicative of the formation of ^{55}Fe -rich aggregates that formed from dissolved organic matter, likely resulting from microbial activity during a phytoplankton bloom. These aggregates scavenged dFe and thereby

made it unavailable to phytoplankton. This process was not observed for the low biomass water, in which Fe released from glacial meltwater and estuarine water was bioavailable to phytoplankton. Glacial meltwaters, even when originating from different geological and redox settings, provided bioavailable Fe to phytoplankton, enhancing Fe uptake rates by a factor of two, compared to the unamended LCW, while groundwater did not. This finding was unexpected, since a previous geochemically based study claimed the bioavailability of Fe in groundwater transported into the coastal zone.

None of the tested Fe chemical speciation parameters (total Fe binding ligand concentration and complexation capacity, concentration of free inorganic Fe) correlated with the Fe uptake rates, measured for the different sources. These results demonstrate the complexity and unpredictability of Fe bioavailability, which is dependent on the source itself and super-imposed by the biogeochemical characteristics of the water to which it is supplied to. This study is the first to demonstrate this interaction. Overall, this study reveals that glacial meltwater and water from the mixing zone of estuaries are bioavailable in low chl regions of the SO, fertilizing phytoplankton blooms and thereby enhancing CO₂ fixation by 80–100 %.

References

Under review:

Stimpfle J, Koch F, Ebner B, et al. Contrasting bioavailability of iron in glacial vs. groundwater to Antarctic phytoplankton: Linking iron uptake to geochemistry, Communications Earth and Environment, doi: <https://doi.org/10.21203/rs.3.rs-7317240/v1>.

SO289 and SO298

Cu speciation in the Equatorial and South Pacific Ocean

Authors

Constructor University | Bremen, Germany

A. Hollister, A. Koschinsky

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

N. Singh

Copper (Cu) can act as a nutrient and/or toxin depending on its speciation and concentration, and is highly complexed to organic ligands (>99%) in the ocean (Buck and Bruland 2005). These ligands can therefore aid in decreasing the bioavailability and toxicity of Cu by lowering the concentration of free Cu ions (Cu^{2+}). The binding strength of these ligands is measured by the stability constants, K (expressed as $\log K$). We analyzed samples for dissolved Cu (dCu), Cu-binding ligand concentrations (L_{Cu}), stability constants ($\log K$) and free Cu^{2+} at selected stations in cruises SO289 (South Pacific Ocean) and SO298 (Equatorial Pacific Ocean) (Figure 1). In addition to the dissolved fraction (<0.2 μm Acropak-filtered), we also filtered and analyzed size-fractionated samples at selected stations, obtained by sequentially-filtering seawater through a 0.015 μm , 0.2 μm and 0.8 μm filter membrane, as well as a 10 kDa (~ 3 nm) ultrafiltration system in the shipboard clean lab. These stations were chosen for analysis to primarily reflect the upwelling regions of both cruises, as well as 1–2 oligotrophic stations each for comparison.

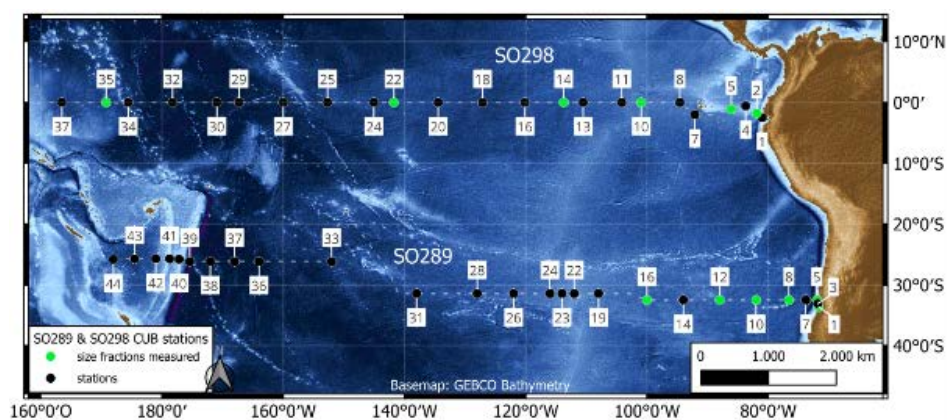


Figure 1: Map of stations for SO289 and SO298 where samples were collected for Cu and/or Cu-speciation via voltammetry. Green symbols represent stations where size-fractionated samples were collected and analyzed for dCu and/or L_{Cu} . Additionally, data for dCu are also presented for all black symbols from SO298.

Cu concentration and speciation were measured on land in a cleanlab at GEOMAR and Constructor University Bremen. For SO298, the dissolved ($0.2 \mu\text{m}$ Acropak-filtered) Cu was primarily analyzed using ICP-MS with SeaFAST preconcentration; several stations for SO298 and SO289 were also measured via voltammetric methods using standard addition. For both SO289 and SO298, Cu-ligand samples, as well as size-fractionated (sequential- and ultrafiltered) Cu concentrations, were analyzed using an automated voltammetry system (Fröhberg et al., 2025) with established methods (Campos and van den Berg 1994). Here, Cu-binding organic ligands and stability constants were measured via competitive ligand exchange adsorptive cathodic stripping voltammetry (CLE-AdCSV). The titration curves were fitted using ProMCC (Omanović et al., 2015) to obtain ligand concentrations and stability constants, as well as free-Cu (Cu^{2+} ions). We initially chose a detection window of $5 \mu\text{mol L}^{-1}$ of the reference ligand salicylaldoxime, which was the same detection window used in the GEOTRACES East Pacific zonal transect GP16 (Ruachoa et al., 2020), although in some samples we were unable to obtain a good curve fit at this concentration.

For SO298, the dCu distribution show minima in the surface waters ($<100 \text{ m}$) of the EPO with concentration ranging (1st to 3rd quartile range) between $0.60\text{--}0.84 \text{ nM}$, suggesting phytoplankton uptake and low atmospheric supply (Figure 2A). In the eastern and central EPO (east of 150°W), dCu distribution exhibited a linear increase down to the deepest sampled depths, ranging from $\sim 1 \text{ nM}$ in the thermocline waters ($\sim 300 \text{ m}$) to $\sim 5 \text{ nM}$ close to the seafloor (Figure 2B). In contrast, the bottom dCu concentrations (below 3500 m) showed relatively low and more uniform levels ($\sim 3.2\text{--}3.5 \text{ nM}$) in the western EPO (west of 160°W). Observed dCu in the thermocline and intermediate waters ($200\text{--}1000 \text{ m}$) was lower than levels calculated using our water mass mixing model, indicating net

scavenging removal along the advective pathways of the water masses. Strong enrichments in dCu were observed in deep waters (>2500 m) of the eastern and central EPO, which could not be explained by water mass mixing and OM remineralization. The variation in particulate Cu indicated a limited influence of reversible scavenging and deep water remineralization, with the supply from sediments likely supporting dCu increase in deep waters. For SO289, fewer stations are presented, concentrated on the upwelling region, but preliminary data show similar general trends (increase at depth) and concentration ranges compared to SO298.

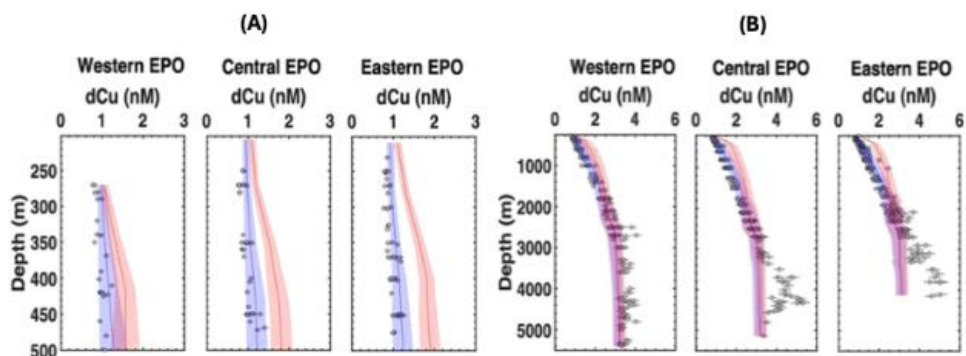


Figure 2: Comparison of observed dCu (solid grey circles) in the (A) thermocline waters (~200–500 m) and (B) full water column (>200 m) with modeled dCu for SO298. The blue solid blue and red lines represent average modeled Cu considering only the influence of water mass mixing and water mass mixing plus organic matter remineralization, respectively. The blue and red patches around the average modeled profiles indicated the estimated uncertainty.

Ligands are sometimes divided into “strong” and “weak” binding classes (Coale & Bruland 1998), although this binding strength classification is defined somewhat arbitrarily. Relatively strong Cu-ligands were detected in excess of dCu in all measured stations on both SO289 and SO298, with logK usually ≥ 12 (Figure 3). However, there was also evidence of a slightly weaker ligand pool for SO289 (logK range: ~10–13) than for SO298 (logK range: ~11–14). The stability constants in SO289 and SO298 were therefore similar or slightly lower than studies in different global regions, including the Northeast Pacific Ocean (11.6–16.5; Whitby et al., 2018), eastern tropical Pacific Ocean (12–14.5; Ruachoa et al., 2020) and the North Atlantic Ocean (12–15; Jacquot & Moffett, 2015). In all cases, free Cu^{2+} (Cu unbound to ligands) remained below potentially toxic concentrations. In both SO289 and SO298, L_{Cu} concentrations and stability constants did not follow specific trends with respect to station or depth.

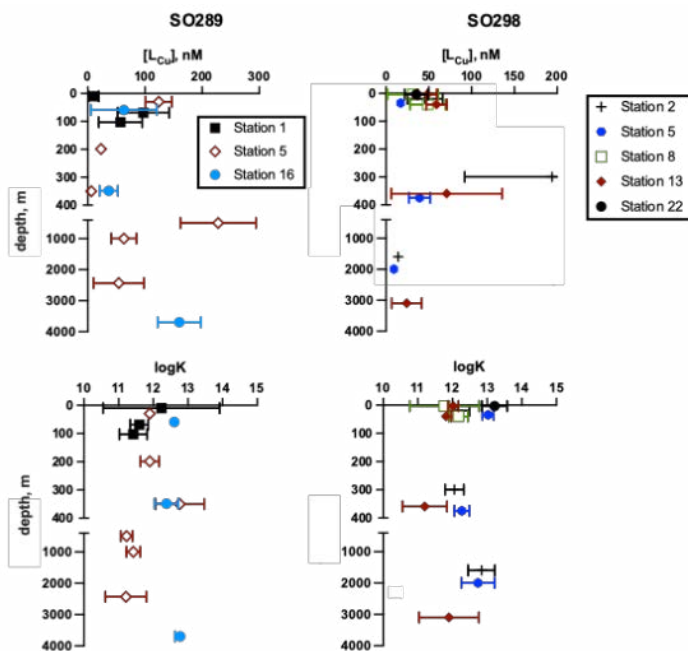


Figure 3: Ligand concentrations (L_{Cu}) and stability constants ($\log K$) in dissolved samples on cruises SO289 and SO298.

Size fractionation of metals and/or metal-binding ligands plays a role in determining the chemical behavior and bioavailability of these metals. For example, colloids can flocculate to form larger particles that incorporate trace metals into them, causing these metals to be removed from the dissolved phase. We selected samples for size-fraction analysis (sequential- and sometimes ultra-filtration) at 3 depths: surface, deep chlorophyll maximum (DCM) and oxygen minimum zone (OMZ)). In most stations, concentrations of dCu and LCu were similar between different size fractions indicating that most Cu and LCu were dominant in the smallest size fractions (fully soluble). Example graphs showing size-fractionated LCu and $\log K$ selected from SO289 and SO298 are shown in Figures 4. In some cases, we were unable to obtain a sufficient curve fit to calculate LCu or K, possibly due to the low concentrations of ligands in seawater, so these data are not shown.

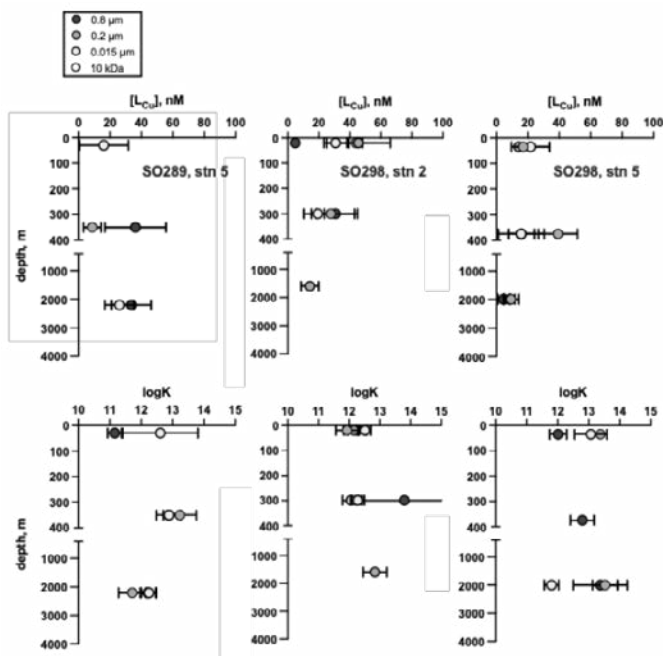


Figure 4: Exemplary data for L_{Cu} and $\log K$ from 3 selected stations on cruises SO289 and SO298.

Acknowledgement

Special thanks to the Captain and crew of R/V Sonne, the scientific team for their dedicated onboard work and the Federal Ministry for Research and Education BMBF for funding for cruises SO289 and SO298.

References

Buck KN & Bruland KW, Copper speciation in San Francisco Bay: a novel approach using multiple analytical windows, *Marine Chemistry* 2005, 96, 185–198, doi: <https://doi.org/10.1016/j.marchem.2005.01.001>.

Campos MLA & van den Berg CMG, Determination of copper complexation in sea water by cathodic stripping voltammetry and ligand competition with salicylaldoxime. *Analytica Chimica Acta* 1994, 284, 481–496, doi: [https://doi.org/10.1016/0003-2670\(94\)85055-0](https://doi.org/10.1016/0003-2670(94)85055-0).

Fröhberg N, Hollister A & Koschinsky K, Simple Automation and Volume Reduction of Voltammetric Measurements for Marine Trace Metal Speciation, *Electroanalysis*, 2025, 37, e70060, doi: <https://doi.org/10.1002/elan.70060>.

Jacquot JE & Moffett JW, Copper distribution and speciation across the International GEOTRACES Section GA03. Deep Sea Research Part II: Topical Studies in Oceanography 2015, 116, 187–207,
doi: <https://doi.org/10.1016/j.dsr2.2014.11.013>.

Ruacho A, Bundy RM, Till CP, Roshan S, Wu J & Barbeau KA, Organic dissolved copper speciation across the US GEOTRACES equatorial Pacific zonal transect GP16, Marine chemistry 2020, 225, 103841,
doi: <https://doi.org/10.1016/j.marchem.2020.103841>.

Whitby H, Posacka AM, Maldonado TM & van den Berg CM, Copper-binding ligands in the NE Pacific, Marine Chemistry 2018, 204, 36–48,
doi: <https://doi.org/10.1016/j.marchem.2018.05.008>.

SO289 and SO298

Distribution and Redox Speciation of Dissolved Vanadium in the South Pacific Ocean and the Equatorial Pacific Ocean

Authors

Constructor University | Bremen, Germany

E. Kurahashi, S. Poehle, A. Koschinsky

Background and objective

Vanadium is known as a redox-sensitive element having three redox species in natural aqueous system. Vanadium, V, is strongly hydrolysed in seawater and is present as tetrahedral vanadate(V) ion $\text{HnVO}_4^{(3-n)-}$. Vanadium(IV) occurs in solution as the vanadyl cation, VO_2^+ in acidic solution below pH 2 and VOOH^+ in slightly alkaline solutions with pH higher than 5.7 (Gustafsson, 2019). In contrast to the oxidized form V(V) the reduced vanadyl V(IV) is highly reactive and forms a large number of strong complexes with inorganic and organic ligands, including humic and fulvic acids and V(V) can potentially even be reduced by humics (Gustafsson, 2019). Vanadium redox species play an important role for biogeochemical cycles in the marine environment because V(V) is an essential nutrient for phytoplankton in the photic zone, forming the metal center of numerous vital enzymes (Nalewajko et al., 1995; Moore et al., 2020). In the oxic marine environment, V is predominantly present as V(V), while the reduced form V(IV) was also detected in coastal water, representing up to 40% of total dissolved V (Wang & Sañudo-Wilhelmy, 2009).

Although several studies of V redox speciation in coastal areas exist, distribution of V redox species in open ocean are largely unknown. To elucidate the distribution of vanadium redox species in the marine environment and their biogeochemical impact including upwelling, hydrothermal input, dust input and nutrients, we have conducted the separation and determination of V redox species in seawater collected in the South Pacific Ocean (SO289, GEOTRACES GP21) and the equatorial Pacific Ocean (SO298, GEOTRACES GP11) (Figure 1).

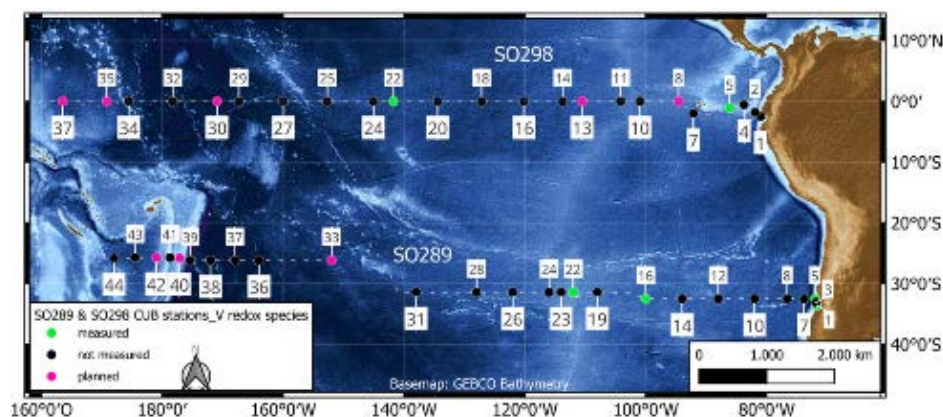


Figure 1: Sampling locations during research cruises SO289 and SO298.

Sample collection and processing

All water samples were taken with a trace metal clean rosette (NISKIN water sampler) equipped with sensors for conductivity, temperature, depth (CTD) and turbidity. The collected water samples in NISKIN bottles were filtered with Acropak 0.2/0.8 μm filter cartridges and subsampled in the clean room on board. All samples were unacidified and kept in frozen until use.

Separation of vanadium redox species have been carried out using a solid phase extraction at Constructor University. 10 mL of sample was loaded on the column filled with chelating resin chelex-100, and V(V) was eluted with ammonium solution (0.1 mol/kg, pH 11) followed by V(IV) elution with nitric acid (0.2 mol/kg, pH 0.8). Determination of V redox species was carried out with an inductively coupled plasma mass spectrometry (ICP-MS) equipped with a kinetic energy discrimination (KED) mode at Constructor University. Detailed description of the separation and determination method of V redox species is given in Kurahashi et al. (2024).

Results and Discussion

Here we present depth distribution of V redox species as well as dissolved oxygen and bio-geological parameters from three stations from SO289 (Figure 2) and two stations from SO298 (Figure 3), which include samples taken in the coastal upwelling and open ocean. Although V(V) was the dominant redox species throughout the entire profiles (16.8–36.6 nmol/kg), V(IV) was also successfully detected (0.9–3.2 nmol/kg).

Coastal upwelling region

Coastal upwelling exists at SO298 station 05 and SO289 station 05, where the dissolved oxygen concentration decreases to less than 20 $\mu\text{mol/kg}$ (Figure 2A and 3A). Despite of the extremely low oxygen, V redox species did not show any correlation with the dissolved oxygen. Furthermore, no notable trends were observed in a ratio of V(IV)/Total V with dissolved organic carbon (DOC) and total nitrogen (TN). However, the concentration of V(IV) decreases with depth in the photic zone, where high concentration of chlorophyll-a and nitrite exist. In the oxygen minimum zone (OMZ), an increase in both V(V) and V(IV) was observed with decreasing dissolved oxygen (100–200 m water depth in SO289 ST05, 250–375 m water depth in SO298 ST05), which is likely due to the release of V redox species during the degradation of organic matter. Additionally, high ratios of V(IV)/Total V appeared at the depth where the dissolved oxygen was less than 100 $\mu\text{mol/kg}$. This suggests a potential preferential release of V(IV) during the organic matter degradation. In deeper water below the OMZ, the ratios of V(IV)/Total V remain nearly constant throughout the water columns.

Open ocean

Although some concentration deviation of V(IV) and V(V) was also observed in the photic zone in open ocean, in general less variations of V(IV) were observed in open ocean seawater relative to coastal seawater (Figure 2B, 2C, 3B). At SO289 station 16, the distributions of V(IV) are divided into two groups, low V(IV) from surface to 400 m water depth (1.5 ± 0.3 nmol/kg) and high V(IV) below 700 m water depth (2.9 ± 0.3 nmol/kg). Although the widely distributed OMZ (less than 100 $\mu\text{mol/kg}$ between 200 and 2000 m water depth) exists in the water column at SO298 station 22, V(IV) remains almost constant (1.3 ± 0.2 nmol/kg) until 2500 m water depth except surface seawater (2.3 ± 0.2 nmol/kg at 21 m water depth).

Deep water

At SO289 station 22, a hydrothermal input derived from East Pacific Rise exists at the seafloor which can be recognized with high turbidity below 2000 m water depth (Figure 2C). The concentration of V redox species varies within the plume, suggesting a significant scavenging of both V(V) and V(IV). Furthermore, slightly higher ratios of V(IV)/Total V demonstrate a preferential uptake of V(V) within the plume. Additionally, some variations of V(V) and V(IV) were observed close to the seafloor in all stations investigated, which may imply the interaction of V redox species between seawater and sediments on the seafloor.

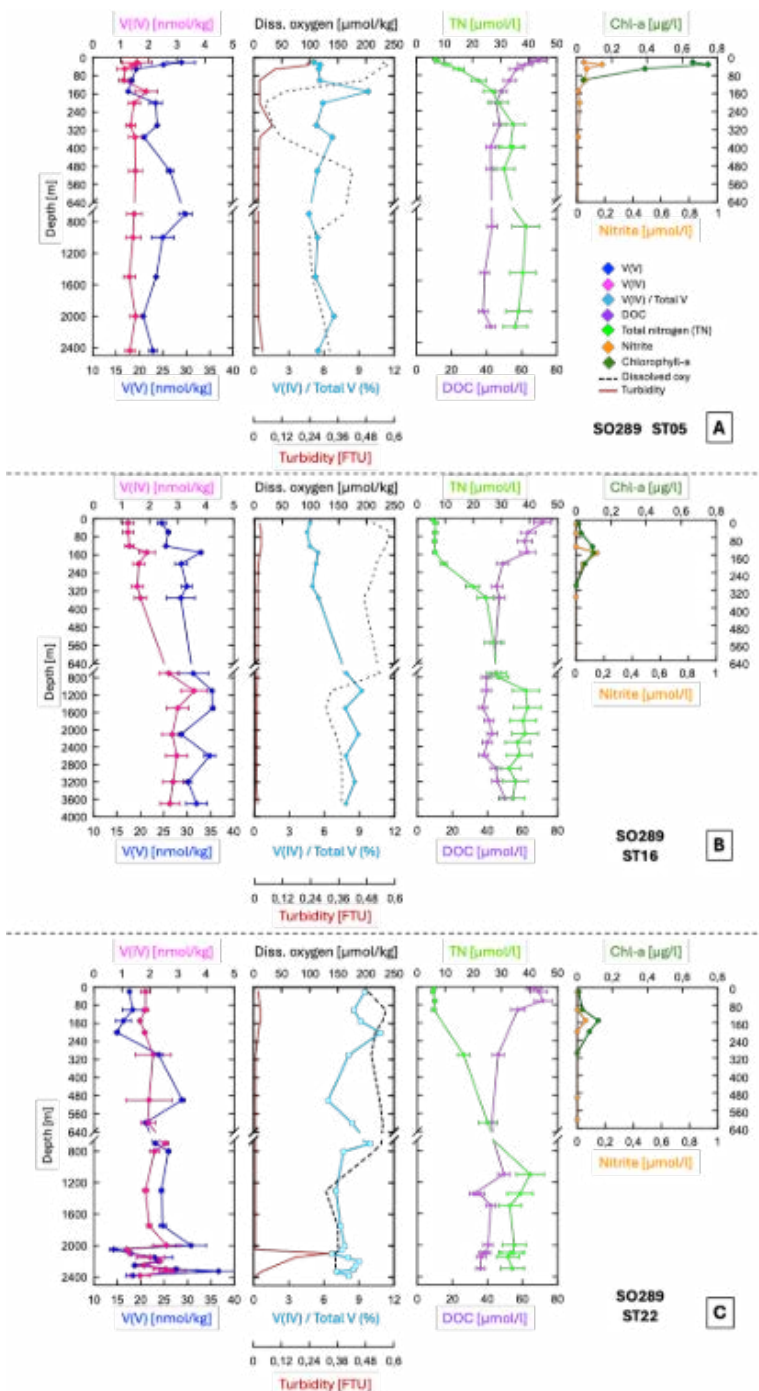


Figure 2: Depth distributions of dissolved V(V) and V(IV) redox species at SO289 station 05 (A), station 16 (B), and station 22 (C). The data points are average values of two replicate samples with the standard deviation. Turbidity, dissolved oxygen and nitrite were taken from the trace metal clean CTD. Dissolved organic carbon (DOC) and total nitrogen (TN) data were from GEOMAR (by M. Gledhill & A. Steffens). Data of chlorophyll-a were from satellite observation (Copernicus Marine Services).

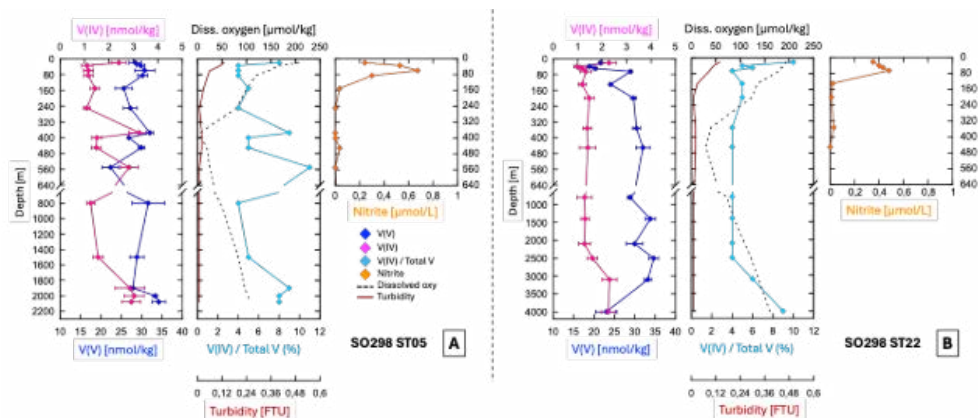


Figure 3: Depth distributions of dissolved V(V) and V(IV) redox species at SO298 station 05 (A) and station 22 (B). The data points are average values of two replicate samples with the standard deviation.

Summary and Outlook

The results obtained indicated V redox species are not subject to control by dissolved oxygen throughout the Pacific Ocean. Scavenging and more complex biogeochemical interactions such as bioavailability at surface seawater and seafloor appear to be key factors for the behavior of vanadium redox species in seawater. Further systematical investigations including size fractionation on V redox species and other biogeochemical data obtained by other teams (e. g. V-isotopes, Cu-binding ligands, Cr redox species, nutrients) will be carried out to elucidate the controlling factors on V redox speciation.

References

- Gustafsson JP, Vanadium geochemistry in the biogeosphere –speciation, solid-solution interactions, and ecotoxicity, *Appl. Geochem*, 2019, 102, 1–25., <https://doi.org/10.1016/j.apgeochem.2018.12.027>.
- Nalewajko C, Lee K, Jack TR, Effects of vanadium on freshwater phytoplankton photosynthesis. *Water Air Soil Pollut.* 1995, 81, 93–105, <https://doi.org/10.1007/BF00477258>.
- Moore EK, Hao J, Spielman SJ, Yee N, The evolving redox chemistry and bioavailability of vanadium in deep time, *Geobiology* 2020, 18, 127–138, <https://doi.org/10.1111/gbi.12375>

Wang D, Sañudo Wilhelmy SA, Vanadium speciation and cycling in coastal waters, *Mar. Chem.* 2009, 117, 52–58, <https://doi.org/10.1016/j.marchem.2009.06.001>.

Kurahashi E, Poehle S, Koschinsky A, Determination of vanadium redox species V(IV) and V(V) in seawater using chelating resin and inductively coupled plasma mass spectrometry, *Deep-Sea Research Part I* 2024, 206, 104261, <https://doi.org/10.1016/j.dsr.2024.104261>.

SO289 and SO298

Does dissolved U and Mo show non-conservative depth distributions along two Pacific transects – SO289 and SO298?

Authors

Constructor University | Bremen, Germany

S. Poehle, I. Pedre, A. Koschinsky

Present address: Institut Dr. Nowak GmbH & Co. KG | Ottersberg, Germany

I. Pedre

Background and objective

In this work, we present the results obtained from the cruises SO298 and SO289, which are both part of the international GEOTRACES program as expeditions GP21 (SO298) and GP11 (SO289). They both started in the east Pacific crossing the Pacific Ocean along the equator (SO298) and at 32°S (SO289). They covered upwelling regions at the west coast of Ecuador (SO298) and Chile (SO289), crossing the East Pacific Rise (EPR) and areas potentially affected by terrestrial input from the Australian continent (Figure 1).

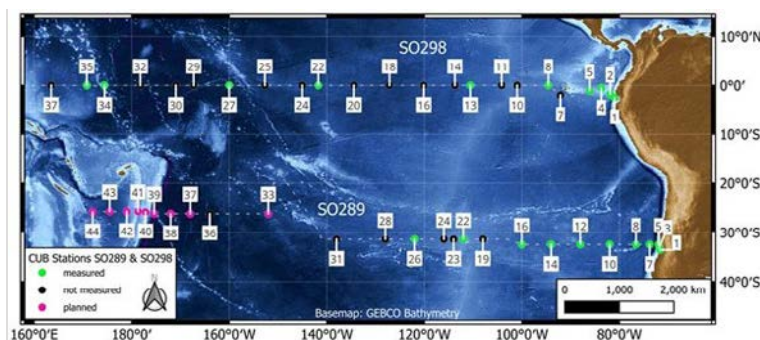


Figure 1: Station map for cruises SO298 (northern transect) and SO289 (southern transect) indicating all stations on which samples for Constructor University have been collected. Their status is colour coded with the measured stations marked in green and planned to be measured stations marked in purple. This map was created with QGIS with data from GEBCO for the bathymetry.

The upwelling feature belongs to the eastern boundary upwelling systems (EBUS) and characterizes the near-coastal water column (Rossi et al., 2009). Due to the upwelled nutrient-rich deep water, these regions experience intense bioproductivity. In consequence, organic matter sinks towards deeper waters and degrades under oxygen consumption, which leads to the observed pronounced oxygen-minimum zones (OMZ, Figure 2).

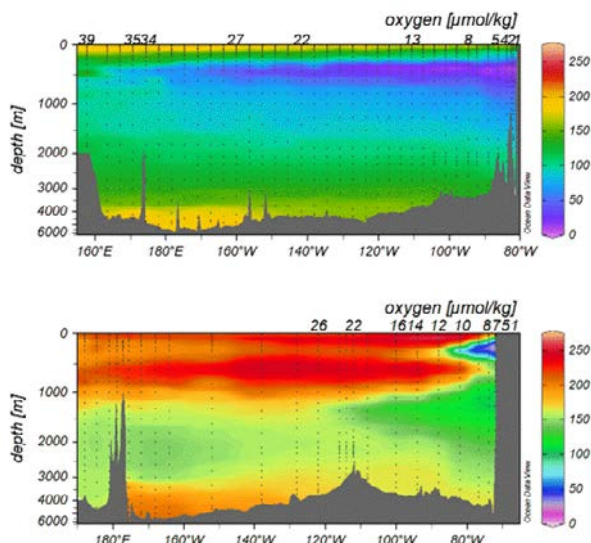


Figure 2: Distribution of dissolved oxygen along the transects of SO298 (A) and SO289 (B) from the American coast towards the West Pacific coastline. Please note that the y-axis (depth) is stretched in the upper part enabling to focus on the oxygen deficient water layers. The same depth range and colour code for oxygen was applied to both section plots. Stations numbers above each plot show the locations of which we present data on trace metals herein. Oxygen data have been recorded with a CTD during up-cast of the trace metal clean water sampler rosette and were provided by GEOMAR.

Molybdenum (Mo) and uranium (U) in seawater have been considered to belong to the group of conservative elements, with 97-105 nmol/kg Mo in the Pacific (Firdaus et al., 2008) and 13.9 ± 0.84 nmol/L (Ku et al., 1977) and 13.60 nmol/kg (Chen et al., 1986) for U given their comparably high dissolved concentration in seawater and their long residence times of 8×10^5 years for Mo (Emerson and Huested, 1991) and $2-5 \times 10^5$ years for U (Hirose & Sugimura, 1991; Ku et al., 1977). However, deviation from this behavior has been reported for Mo in specific areas such as in upwelling regions (Ho et al., 2018).

Both metals are redox-sensitive trace elements, and their characteristics differ according to their redox-state. While the hexavalent species of Mo is highly soluble (Sohrin et al., 1999) the reduced species tends to form solid particulates under oxygen-deficient and euxinic conditions. Since Mo and U are elements of the same subgroup, the oxidized and reduced U species show similar physical-chemical properties compared to Mo.

Each process, e. g. sorption or reduction, is known to change the isotopic compositions (Barling & Anbar, 2004; Wasylenki et al., 2008), making the understanding of redox-sensitive metals such as Mo and U a prerequisite for the interpretation of isotopic data.

The OMZs covered by SO298 and SO289 are of specific interest for Mo and U due to their redox-sensitive nature. To reveal deviations from conservative depth patterns, we also included rubidium (Rb) as a representative for truly conservative behavior.

Besides, other features such as the hydrothermal plume emanating from the East Pacific Rise and dust input from the Australian continent will be evaluated for their impact on the distribution of dissolved Mo and U in the Pacific Ocean.

Sample collection and processing

All samples were collected with a trace metal-clean rosette water sampler (provided by GEOMAR) which was equipped with a CTD-unit. After the rosette was lifted on-deck, the individual water samplers (Niskin bottles) were brought into the clean laboratory container. Filtration through capsules (AcroPak, 0.8/0.2 μm) and subsampling was performed herein.

For selected stations and depths, we applied a sequential filtration on unfiltered samples under a clean bench which was set-up in a ship's lab to reduce the potential risk of contamination while sample handling. We used filters with pore sizes of 0.8, 0.2 and 0.015 μm and selected three individual depths at specific stations to cover surface waters, the OMZ, and a water mass sufficiently far below the OMZ.

Additionally, an ultrafiltration using a 10 kDa membrane (equals to approx. 3 nm pore size) was performed on samples collected within the OMZ at some stations where the sequential filtration was performed.

All seawater samples were acidified under a clean bench to 0.02 mol/L HCl (ultrapure grade).

Samples were stored cool and dark until analysis in the home laboratory at Constructor University. After a 100 x dilution in diluted nitric acid, the measurement was performed on a quadrupole inductively coupled-mass spectrometer (ICP-MS).

Results and Discussion

The SO298 cruise started from Ecuador covering an upwelling area with a far-reaching oxygen minimum zone (up to 145°W). We normalized our data to salinity with S=35 enabling to highlight features which are not water mass dependent.

We observe slightly lower Mo and U concentrations in the eastern Pacific basin compared to higher concentrations observed in the western Pacific basin. Although those differences are not analytically significant, they seem to reflect a specific pattern.

To identify significant differences in our concentration data we applied a range given by 2 x SD of replicate measurements of a certified reference material (NASS-7 and IAPSO).

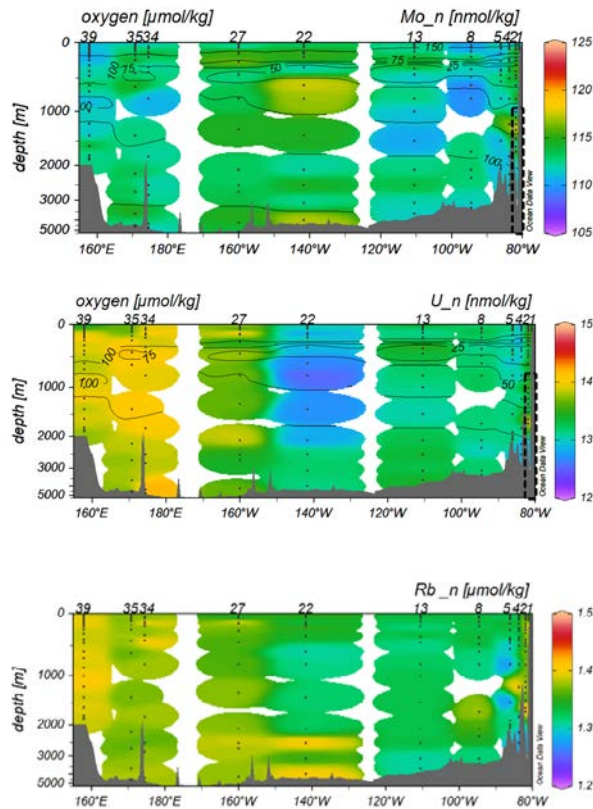


Figure 3: Distribution of dissolved ($<0.2 \mu\text{m}$) salinity-normalized Mo (upper-most plot), U (middle plot), and Rb (bottom plot) along the SO298 transect. Trace metal data shown here are normalized to salinity of 35. Station numbers are given above each plot while dissolved oxygen is shown as contour lines in the Mo and U plots. The dashed square highlights areas of significant deviation from a conservative distribution.

This approach reveals that Mo is slightly elevated at the shallow stations 1 (located above the shelf) and in deeper waters between 1000 and 2000 m water depth at station 2 (located right off the shelf edge). Dissolved U shows slightly higher concentrations between 1500 and 2000 m water depth in close vicinity to underwater seamounts (Figure 3). This hints towards mechanisms releasing Mo and U at the shallow shelf station but also in deeper waters either due to remineralization processes of organic matter or from lithogenic sources.

Our data obtained from the sequential filtration of samples collected in surface waters (21 m), in the OMZ (203 m), and in deep water masses (1608 m) at station 2 show that Mo and U are present in the truly dissolved phase, $<0.015 \mu\text{m}$ (Figure 4).

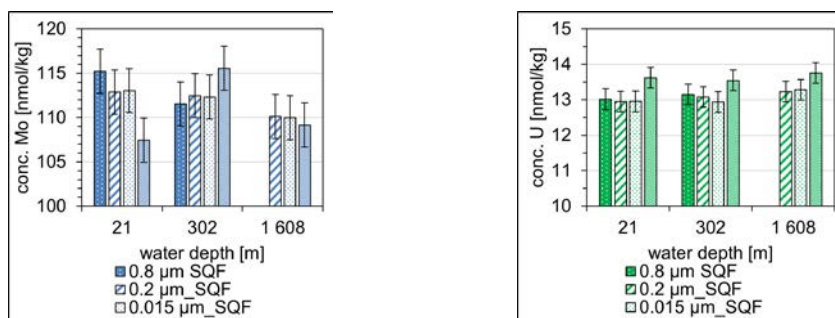


Figure 4: SO298_Station 5: Distribution of Mo (left) and U(right) in different size fraction: >0.8 $\mu\text{m\_SQF}$, between 0.8 and 0.2 $\mu\text{m\_SQF}$, < 0.015 $\mu\text{m\_SQF}$, <0.2 $\mu\text{m\_clean lab}$ for comparison.

The OMZ along the SO289 South Pacific transect was less extended compared to the equatorial transect (figure 2) though the oxygen concentration ranges were similar with an averaged minimum of 12 $\mu\text{mol/kg}$. However, the depth distribution for U was opposite with low concentrations in the water depths of the OMZ (Figure 5). The sequential filtration revealed no significant difference between the investigated size fractions with dissolved U mostly present in the truly dissolved fraction (<0.015 μm , Figure 6). The observed slightly lower U concentrations in the depth range of the OMZ might be attributed to sorption or uptake. The analysis of the particulate material collected during the sequential filtration will help to understand the related processes.

Data for Mo are still incomplete though we observe lower concentrations at the near-shore station (station 5) compared to the open ocean station (station 16), while the distribution of Rb along that transect is conservative within the pre-defined range of 2 x SD of the CRM (Figure 5).

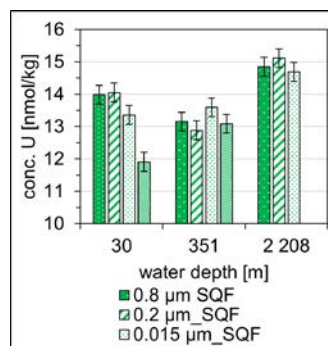
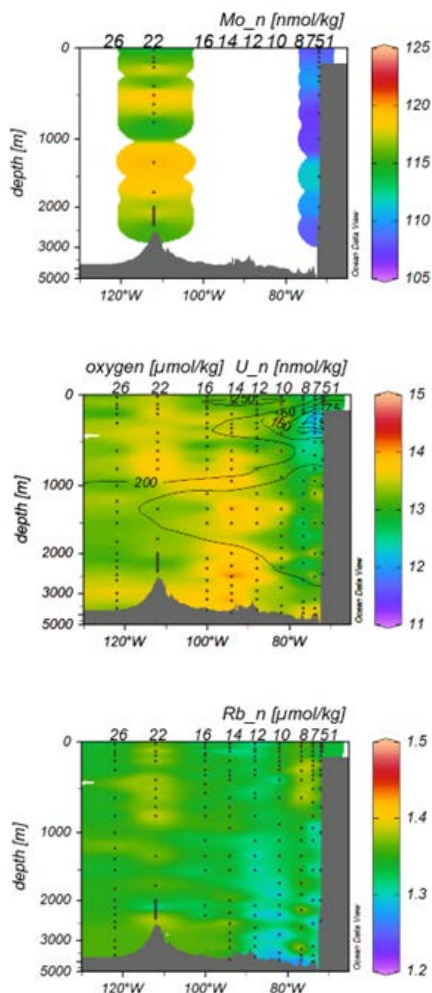


Figure 5 (3 left): Distribution of salinity normalized dissolved Mo (top), U (middle) and Rb (bottom) between the Chilean coast and 125°W covering the upwelling region and the EPR (station 22). Please note the stretched upper part of the depth (y) axis and the oxygen overlay indicated by dark contour lines in the U plot. Figure 6(right): SO289_Station 5: Distribution of U in different size fractions: >0.8 μm_SQF, between 0.8 and 0.2 μm_SQF, < 0.015μm_SQF, <0.2μm_clean lab for comparison.

To conclude, dissolved Mo and U display mostly conservative behaviour though slight deviations have been observed in near-coastal upwelling areas in the East Pacific Ocean.

In the eastern equatorial Pacific (SO298) Mo and U show slightly higher concentrations between 1000 and 1500 m water depth compared to the average concentration of the investigated transect. They are both present in the size fraction smaller than 0.015 μm and we assume that either dissolution of sinking particulate matter or release from the sediment cause the observed slight increase in concentration.

In the upwelling area investigated in the South Pacific Ocean (SO289), U and Mo are slightly depleted in the water depth of the OMZ and throughout the water column for Mo. The sequential filtration revealed that both metals are present in the truly dissolved size fraction ($<0.015\ \mu\text{m}$). Although the oxygen concentration in the OMZ was similarly low in both cruises, it is not the only factor controlling the distribution of Mo and U as can be seen by the opposing near-coastal patterns. Along both transects, Rb displays conservative patterns which helps to reveal slight deviations for U and Mo.

References

- Barling J & Anbar AD, Molybdenum isotope fractionation during adsorption by manganese oxides, *Earth Planet Sci Lett* 2004, 217, 315–329, [https://doi.org/10.1016/S0012-821X\(03\)00608-3](https://doi.org/10.1016/S0012-821X(03)00608-3).
- Chen JH, Lawrence Edwards R & Wasserburg GJ, ^{238}U , ^{234}U and ^{232}Th in seawater, *Earth and Planetary Science Letters* 1986, 80, 241–251.
- Emerson SR & Huested SS, Ocean anoxia and the concentrations of molybdenum and vanadium in seawater, *Mar Chem* 1991, 34, 177–196, [https://doi.org/10.1016/0304-4203\(91\)90002-E](https://doi.org/10.1016/0304-4203(91)90002-E).
- Firdaus ML, Norisuye K, Nakagawa Y, Nakatsuka S & Sohrin Y, Dissolved and labile particulate Zr, Hf, Nb, Ta, Mo and W in the western North Pacific Ocean, *J Oceanogr* 2008, 64, 247–257, <https://doi.org/10.1007/s10872-008-0019-z>.
- Hirose K & Sugimura Y, CHEMICAL SPECIATION OF PARTICULATE URANIUM IN SEAWATER, *Journal of Radioanalytical and Nuclear Chemistry* 1991, Articles 149, 83–96.
- Ho P, Lee JM, Heller MI, Lam PJ & Shiller AM, The distribution of dissolved and particulate Mo and V along the U.S. GEOTRACES East Pacific Zonal Transect (GP16): The roles of oxides and biogenic particles in their distributions in the oxygen deficient zone and the hydrothermal plume, *Mar Chem* 2018, 201, 242–255, <https://doi.org/10.1016/j.marchem.2017.12.003>.
- Ku TL, Knauss KG & Mathieu GG, Uranium in open ocean: concentration and isotopic composition, *Deep-Sea Research* 1977, 24, 1005–1017, [https://doi.org/10.1016/0146-6291\(77\)90571-9](https://doi.org/10.1016/0146-6291(77)90571-9).
- Sohrin Y, Matsui M & Nakayama E, Contrasting behavior of tungsten and molybdenum in the Okinawa Trough, the East China Sea and the Yellow Sea, *Geochim Cosmochim Acta* 1999, 63, 3457–3466.

Rossi V, López C, Hernández-García E, Sudre J, Garçon V & Morel Y, Surface mixing and biological activity in the four Eastern Boundary upwelling Systems, *Nonlinear processes in Geophysics* 2009, 16, 557–568.

Wasylenki LE, Rolfe BA, Weeks CL, Spiro TG & Anbar AD, Experimental investigation of the effects of temperature and ionic strength on Mo isotope fractionation during adsorption to manganese oxides, *Geochim Cosmochim Acta* 2008, 72, 5997–6005, <https://doi.org/10.1016/j.gca.2008.08.027>.

SO289 and SO298

High Field Strength Elements (Zr, Nb, Hf): Distributions in the Pacific Ocean from GEOTRACES

Authors

Constructor University Bremen gGmbH | Bremen, Germany

P. Tselykh, S. Poehle, E. Kurahashi, A. Koschinsky

Introduction

High field strength elements (HFSEs) such as zirconium (Zr), niobium (Nb), and hafnium (Hf) are increasingly recognized as valuable tracers of physical and chemical processes in the ocean. Their extremely low dissolved (d) concentrations in seawater (dZr: 7–380 pmol/kg, dNb: 0.9–30 pmol/kg, dHf: 0.09–1 pmol/kg; Tanaka et al., 2019; Ueki et al., 2023) and instability in solution without hydrofluoric acid (HF) make both storage and analysis technically challenging. In addition, previously published datasets show systematic differences (Ueki et al., 2023), suggesting that methodological uncertainties remain. Previous studies (Frank, 2011; Schmidt et al., 2014; Poehle et al., 2017; Ueki et al., 2023) indicate that HFSEs may reflect processes such as particle scavenging, remineralization, and large-scale water mass circulation. Here we present results from seawater samples collected during GEOTRACES cruises SO289 (GP21, South Pacific) and SO298 (GP11, Equatorial Pacific), analyzed using a newly developed SeaFAST offline preconcentration method at Constructor University.

Sample collection and processing

Seawater samples from cruises SO289 (GP21) and SO298 (GP11) were collected using a trace-metal-clean titanium CTD rosette from GEOMAR. After recovery, the samples were transferred into a clean container and filtered through Acropak filter (0.2/0.8 μm) into 100 LDPE bottles. The bottles were acid-cleaned in advance according to GEOTRACES protocols for trace metal sampling to reduce the risk of contamination. The samples were then acidified on board with ultrapure HCl to a

final concentration of 0.02 M for storage. After arrival at the Constructor University Geochemistry laboratory, they were further acidified with ultrapure HF to a final concentration of 0.002 M and stored for several months to ensure complete dissolution and stabilization of HFSEs.

The sampling stations for both cruises, including analyzed and planned profiles for HFSE determinations, are shown in Figure 1.

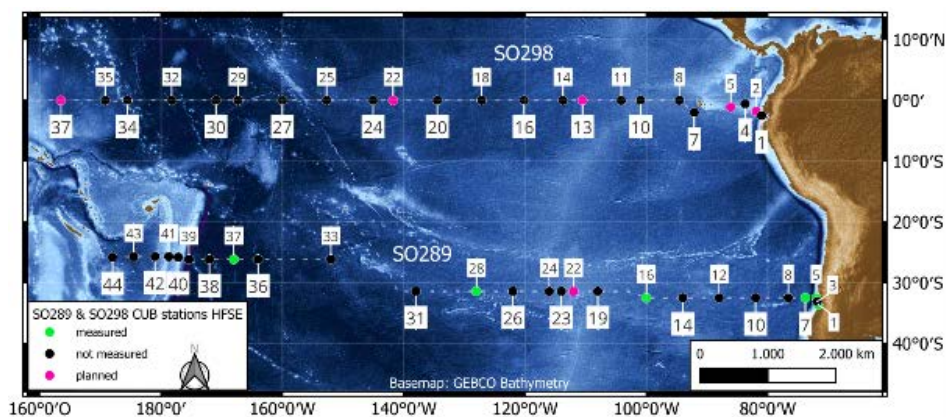


Figure 1: Sampling stations of GEOTRACES cruises SO289 (GP21, South Pacific) and SO298 (GP11, Equatorial Pacific), showing locations of analyzed and planned profiles for HFSE.

Analytical method

A new SeaFAST offline preconcentration method was developed and optimized at the Constructor University Geochemistry Laboratory for reliable HFSE determination. In contrast to other published methods (Firdaus et al., 2007; Firdaus et al., 2018; Tanaka et al., 2019; Ueki et al., 2023), the new approach utilizes significantly lower concentrations of HF, thereby improving safety for laboratory personnel. Additionally, compared to the online SeaFAST approach (Poehle et al., 2015), the offline configuration minimizes disruption to ICP-MS workflows, increasing instrument availability for other users. The method employs NOBIAS Chelate-PA1 resin, which effectively retains HFSEs while removing major cations. Column conditioning was performed with a 3.5 mol/kg ammonium acetate buffer at pH 6.0 ± 0.05 , and the optimized elution mixture of 1.5 mol/kg HNO_3 with 0.05 mol/kg HF was used to ensure efficient recovery of the target elements. This configuration was selected after testing different buffer pH values and elution acid compositions, with the final setup providing stable calibration curves and reproducible recoveries for Zr, Nb, and Hf. The potential extension of this method for tantalum (Ta) is currently under evaluation.

To assess the accuracy of ICP-MS measurements, the certified reference material SLRS-6 (National Research Council Canada) was analysed directly, without preconcentration, and compared to published data (Ebeling et al., 2022). In addition, the seawater reference material NASS-7 was preconcentrated using the SeaFAST method together with the samples. Since no CRM is certified specifically for HFSEs in seawater, the results for NASS-7 were evaluated against previously reported values (Ueki et al., 2023). These interlaboratory comparisons demonstrate that the offline preconcentration method provides reliable and reproducible measurements of Zr, Nb, and Hf in seawater. The detection limits of the new method in seawater are 7 pmol/kg for Zr, 0.25 pmol/kg for Nb, and 0.15 pmol/kg for Hf, calculated as three times the standard deviation of replicate preconcentrated seawater samples.

While only SO289 samples have been analysed so far, a subset of SO298 samples has already been preconcentrated and prepared for analysis. Measurements of these samples are planned but not yet available at the time of this abstract.

Results

The vertical profiles of dissolved Zr, Hf, and Nb from SO289 stations (Figure 2) show clear differences in their depth distributions. Both Zr and Hf display increasing concentrations with depth, suggesting inputs from sinking particle dissolution or processes related to deep-water circulation. In contrast, Nb exhibits a relatively uniform vertical distribution with higher variability compared to Zr and Hf, pointing to distinct sources and sinks for this element.

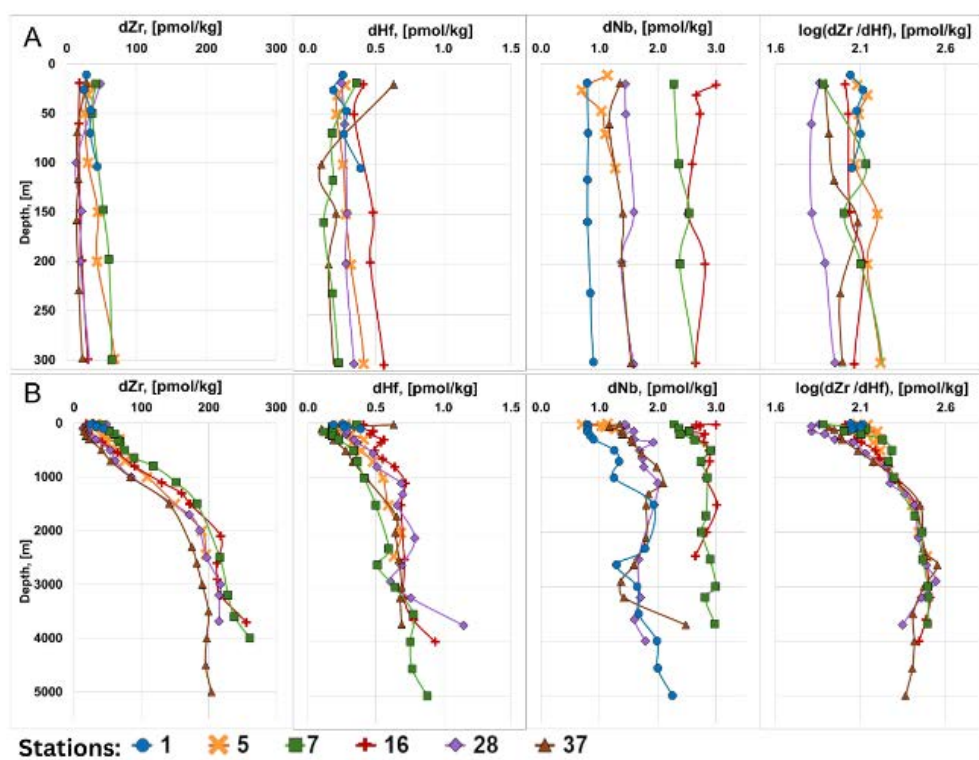


Figure 2: Vertical profiles of dissolved Zr, Hf, and Nb: (A) upper 300 m; (B) full-depth distribution across SO 289 stations.

Strong correlations between dissolved Zr and Hf with silicate are observed (Figure 3 A and B). Especially for Zr, concentrations rise proportionally with silicate, while Hf follows the trend more weakly. Correlations with phosphate and nitrate are present but likely reflect secondary co-variation with silicate rather than a direct relationship. The increase of the dZr/dHf ratio with both depth and silicate concentration further supports the interpretation that Zr is enriched relative to Hf in silicate-rich, deeper waters.

Differences between profiles from various SO289 stations are evident, with some stations showing stronger enrichments in Zr and Hf in deeper waters than others. These differences may reflect spatial variability in particle fluxes or remineralization intensity across the sampled regions. In contrast, Nb does not show systematic enrichment with depth but still exhibits notable variations between profiles. This distinct behavior highlights that Nb is likely controlled by different processes than Zr and Hf. Additional data from more stations, as well as forthcoming analyses of Ta – the geochemical twin of Nb – will help to clarify the factors controlling dissolved Nb and Ta concentrations and explain why their distributions differ from those of Zr and Hf.

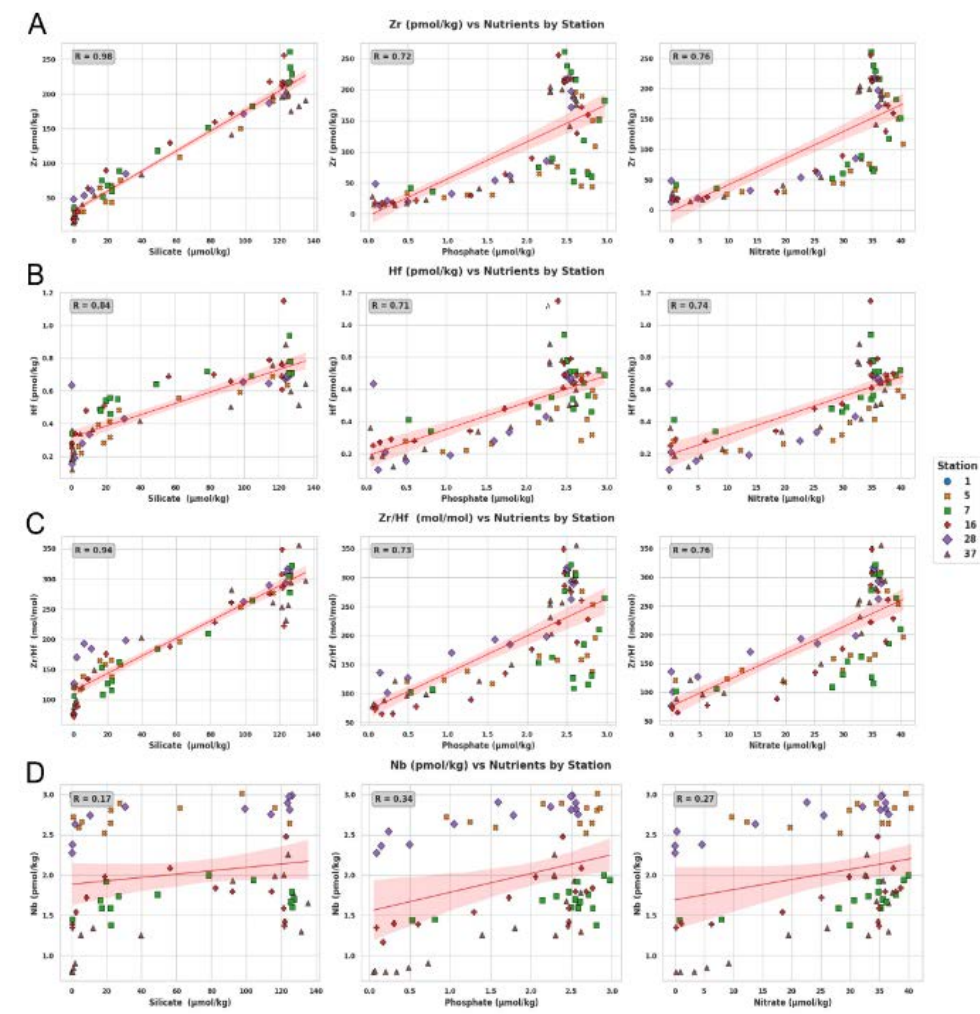


Figure 3: Concentrations of dZr (A), dHf(B), ratio of dZr/dHf (C) and concentrations of dNb (D) plotted against nutrient levels (silicate, phosphate, nitrate). R is Pearson correlation coefficient between element concentration or ratio and nutrient concentration.

Conclusion

This study provides new insights into the distribution of high field strength elements (HFSEs) in the South Pacific Ocean from GEOTRACES cruise SO289, using a newly developed offline SeaFAST preconcentration method with ICP-MS.

Zr and Hf show enrichment with depth, strong correlations with silicate, and increasing Zr/Hf ratios, suggesting links to remineralization and particle cycling. The Zr/Hf ratio itself may serve as a tracer for processes associated with silicate

cycling. In contrast, Nb shows relatively uniform vertical distributions and no significant correlation with nutrients, indicating a distinct geochemical behavior with a more conservative distribution.

These results highlight the potential of Zr and Hf as tracers of oceanic processes, while Nb provides complementary information but is less tightly linked to nutrient dynamics. Ongoing analyses of hydrothermal and bottom-influenced stations will refine the understanding of HFSE sources and sinks.

Future work will include the analysis of preconcentrated samples from SO298, as well as additional stations from SO289. This will extend the dataset into the Equatorial Pacific and provide further insights into the influence of hydrothermal inputs and circulation on HFSE distributions.

References

Ebeling A, Zimmermann T, Klein O, Irrgeher J & Prärock D, Analysis of seventeen certified water reference materials for trace and technology-critical elements, *Geostandards and Geoanalytical Research* 2022, 46(2), 351–378, <http://dx.doi.org/10.1111/ggr.12422>.

Firdaus LM, Mashio AS, Taejin KIM, Muhammad R, McAlister JA, Obata H, Gamo T & Khaydarov R, Simultaneous measurement of picomolar zirconium, hafnium, niobium and tantalum in seawater using commercially available chelating resin and subsequent ICP-MS determination, *Geochemical Journal* 2018, 52(5), 427–431, <https://doi.org/10.2343/geochemj.2.0533>.

Firdaus ML, Norisuye K, Sato T, Urushihara S, Nakagawa Y, Umetani S & Sohrin Y, Preconcentration of Zr, Hf, Nb, Ta and W in seawater using solid-phase extraction on TSK-8-hydroxyquinoline resin and determination by inductively coupled plasma-mass spectrometry, *Analytica Chimica Acta* 2007, 583(2), 296–302, <https://doi.org/10.1016/j.aca.2006.10.033>.

Frank M, Chemical twins, separated, *Nature Geoscience* 2011, 4, 220–221, <https://doi.org/10.1038/ngeo1125>.

Poehle, S, Schmidt, K & Koschinsky A, Determination of Ti, Zr, Nb, V, W and Mo in seawater by a new online-preconcentration method and subsequent ICP-MS analysis, *Deep-Sea Research Part I: Oceanographic Research Papers* 2015, 98, 83–93, <https://doi.org/10.1016/j.dsr.2014.11.014>.

Poehle S & Koschinsky A, Depth distribution of Zr and Nb in seawater: The potential role of colloids or organic complexation to explain non-scavenging-type behavior, *Marine Chemistry* 2017, 188, 18–32, <https://doi.org/10.1016/j.marchem.2016.12.001>.

Schmidt K, Bau M, Hein J R & Koschinsky A, Fractionation of the geochemical twins Zr-Hf and Nb-Ta during scavenging from seawater by hydrogenetic ferromanganese crusts, *Geochimica et Cosmochimica Acta* 2014, 140, 468–487, <https://doi.org/10.1016/j.gca.2014.05.036>.

Tanaka Y, Tsujisaka M, Zheng L, Takano S & Sohrin Y, Application of NOBIAS Chelate-PA 1 resin to the determination of zirconium, niobium, hafnium, and tantalum in seawater, *Analytical Sciences* 2019, 35, 1015–1020, <https://doi.org/10.2116/analsci.19P069>.

Ueki R, Zheng L, Takano S & Sohrin Y, Distributions of zirconium, niobium, hafnium, and tantalum in the subarctic North Pacific Ocean revisited with a refined analytical method, *Geochemical Journal* 2023, 57(5), 143–154, <https://doi.org/10.2343/geochemj.GJ23013>.

SO289 and SO298

Chromium Redox Speciation in Oxygen Minimum Zones in the South (SO289/GP21) and Equatorial (SO298/GP11) Pacific Ocean

Authors

Constructor University | Bremen, Germany

N. van Horsten, A. Koschinsky, S. Pöhle

Introduction

During the SO289/GP21 (Achterberg et al., 2022) and SO298/GP11 (Achterberg & Singh, 2023) cruises in the South and Equatorial Pacific Ocean, respectively, seawater samples were collected for chromium (Cr) redox speciation analysis as part of the international GEOTRACES programme (Figure 1).

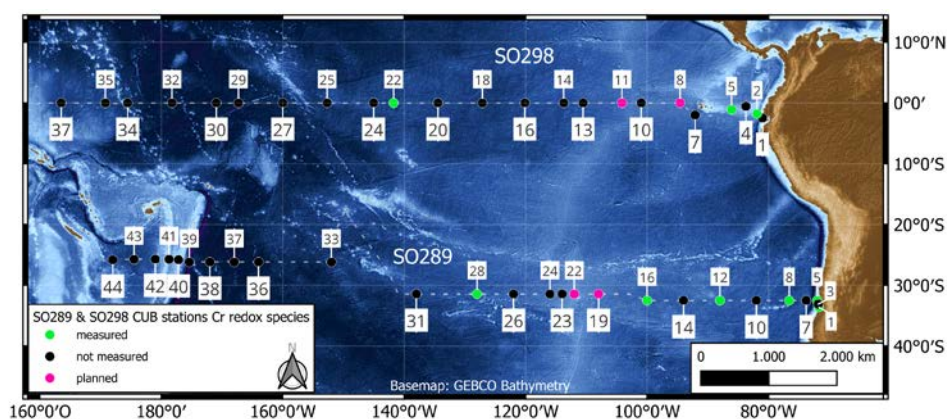


Figure 1: Sampling and analysis map for the Constructor University group and specifically Cr redox speciation, during the SO289 and SO298 cruises.

Cr is a redox-sensitive trace metal in the marine system, where its redox species differ in their properties and the abundance of these species can be influenced by different environmental conditions. The hexavalent species, Cr(VI), occurs in dissolved form in the seawater column, while the reduced species, Cr(III), is particle-reactive and easily sorbs to particulate material. Thermodynamically, the hexavalent species is the more stable under oxic conditions. However, significant concentrations of Cr(III) have also been detected in oxic waters, higher than what is theoretically expected according to its thermodynamic stability. The pronounced oxygen minimum zone (OMZ) off the Chilean and Ecuadorean coast is therefore of particular interest to investigate the depth distribution of Cr in comparison to the oxygen-rich open ocean. Since the redox species of this trace metal differ in their characteristics, the abundance of the different species might be affected by various environmental controls and inputs.

Methodology

The concentration of the Cr redox species in seawater is in the nanomolar range. By using the voltammetric analytical technique, adsorptive cathodic stripping voltammetry, we are able to measure Cr redox speciation in seawater down to the in-situ nanomolar concentrations expected, with the precision required to observe variations due to changes in environmental factors (Sander & Koschinsky, 2000). Firstly, the untreated sample was analysed for Cr(VI) and then the UV digested sample was analysed for total Cr, thereby allowing for the calculation of the Cr(III) concentration by difference. Analysis was done using a Metrohm Computrace voltammeter, with a hanging mercury drop electrode as the working electrode, an Ag/AgCl₃ (3M KCl) reference electrode and a carbon auxiliary electrode. All chemicals used were suprapure grade for reagents and ultrapure grade for the treatment of the samples. High purity nitrogen gas (99.999%) was used for the purging of the sample prior to analysis. For the analysis of the sample 0.15M diethylenetriaminepentaacetic acid was used as the complexing agent in 1M acetate buffer (pH 5.5), and NaNO₃ as the reaction catalyst. Cr(VI) concentrations were determined across a 3-fold standard addition analysis. The method was optimized for sample analysis (Pađan, et al., 2019) with a mean blank concentration of 0.13nM and a detection limit of 0.53nM. Voltammograms were post processed using ECDSoft software (Omanović & Pižeta, 2016).

Results and Discussion

Total Cr concentrations ranged from 1.79 to 5.17 nM, Cr(VI) concentrations ranged from <0.53 to 5.13 nM and Cr(III) concentrations ranged from <0.53 nM to 2.33 nM, during the SO289 cruise in the South Pacific Ocean. The influence of the OMZ on the Cr(VI)/Cr(III) ratio can be observed at stations 1, 5, 8 and 12 (Figure 2), where a

decrease in Cr(VI)/Cr(III) occurs as the oxygen concentration decreases. As the OMZ weakens from station 1 to 12, the concurrent change also weakens and is not visible in the open ocean stations, 16 and 28, where no noticeable OMZ is present.

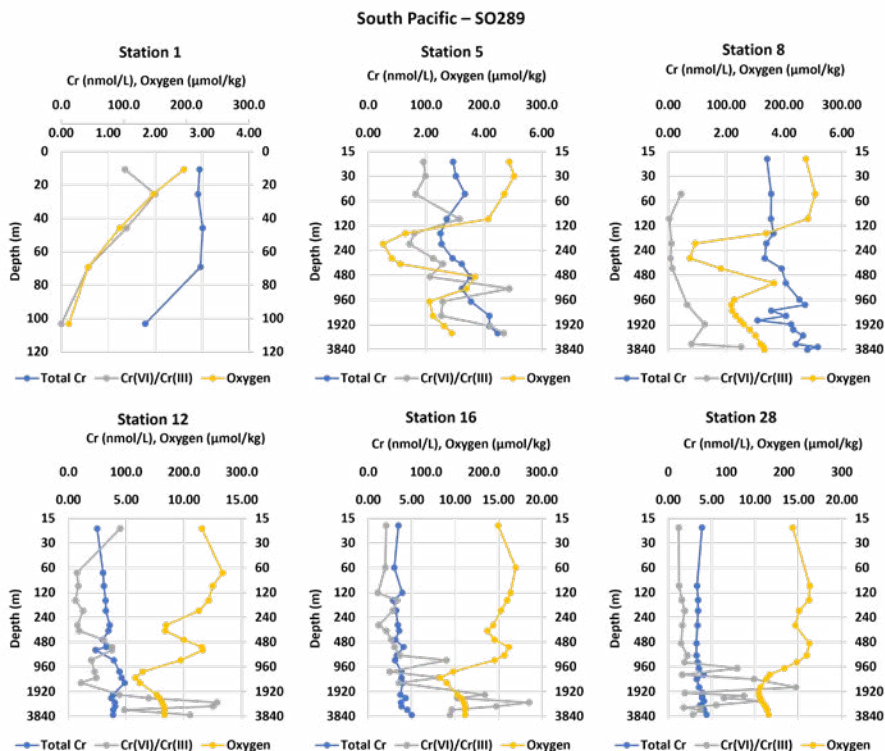


Figure 2: Cr concentration profiles of 6 stations sampled during the SO289 cruise. Stations 1, 5, 8 and 12, sampled in the coastal and offshore upwelling zone along the Chilean coast, where the OMZ was sampled. Stations 16 and 28, sampled in the eastern and western open ocean, respectively. Total Cr in blue, Cr(VI)/Cr(III) in grey and oxygen in yellow.

Size fractionated analysis was conducted on selected samples; these results do not yet show a clear trend in size fractionation between the two Cr redox species (Figure 3). At station 1, size fractionated analysis was done on the bottom water sample, where no detectable Cr(VI) was present. At station 5, where size fractionated analysis was done on surface, OMZ and deep-water samples, no change in Cr(VI)/Cr(III) was observed in the surface and OMZ waters between 0.8, 0.2 and 0.015 μm . An increase in Cr(VI)/Cr(III) is observed in the ultrafiltered OMZ sample, as well as in the 0.2 and 0.015 μm fractions of the deep-water sample, where we also observe an increase in the Cr total and redox species concentrations with increasing size fraction.

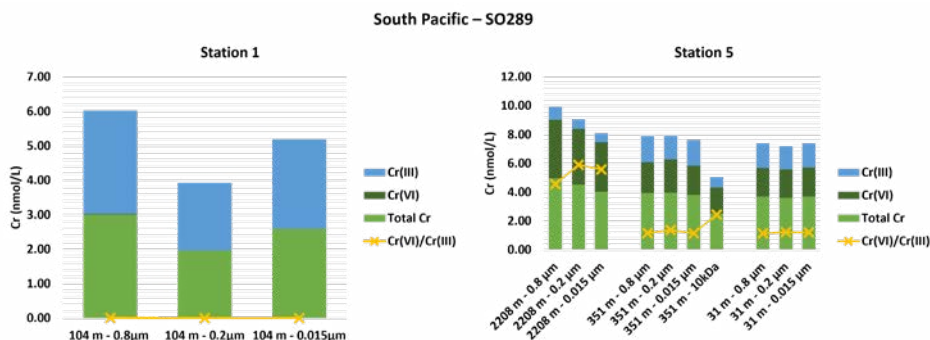


Figure 3: Cr concentrations of samples filtered sequentially through 0.8µm, 0.2µm, 0.015µm, and ultrafiltration of 10kDa. Station 1: bottom water sample; Station 5: surface water, water from the OMZ and bottom water. Total Cr in light green, Cr(VI) in dark green, Cr(III) in blue and Cr(VI)/Cr(III) in yellow.

Total Cr concentrations ranged from 2.41 to 8.68 nM, Cr(VI) concentrations ranged from 2.32nM to 6.00 nM and Cr(III) concentrations ranged from <0.53 nM to 3.93 nM, during the SO298 cruise in the Equatorial Pacific Ocean. The concurrent change in the Cr(VI)/Cr(III) ratios with oxygen concentrations can also be observed in the OMZ in the Equatorial Pacific as is observed in the South Pacific. The influence of the OMZ in the Equatorial Pacific is however far-reaching and is also observed at station 22, in the open ocean, due to the extensive mixing of the oxygen depleted waters out into the open ocean, by the equatorial under current (Figure 4).

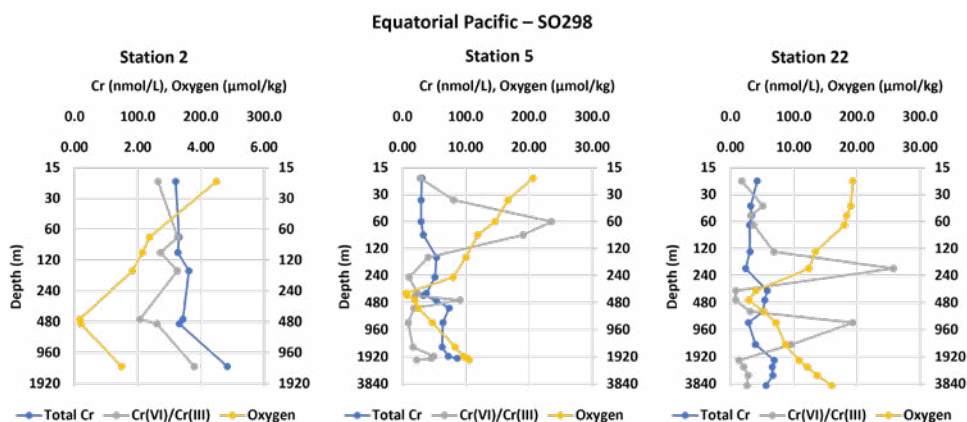


Figure 4: Cr concentration profiles of 3 stations sampled during the SO298 cruise. Stations 2 and 5, sampled in the upwelling region along the Ecuadorean coast, and station 22, sampled in the open ocean. Total Cr in blue, Cr(VI)/ Cr(III) in grey and oxygen in yellow.

Currently only one sample in the surface water at station 5 of SO298 was analysed for size fractionation. The overall Cr concentrations is slightly higher in the largest size fraction ($> 0.8 \mu\text{m}$). An increase in Cr(VI)/Cr(III) is evident in the $0.2 \mu\text{m}$ size fraction compared to both the 0.8 and $0.015 \mu\text{m}$ size fractions. Size fractionation of Cr and its redox species will be further investigated as analysis of more samples is completed.

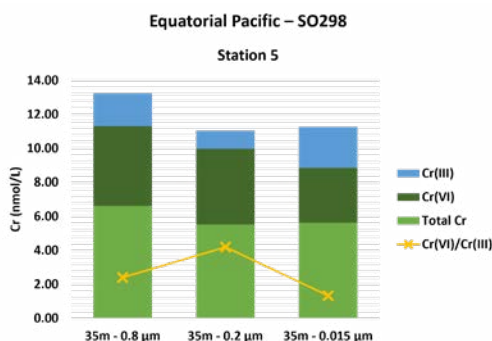


Figure 5: Cr concentrations of a surface water sample from station 5, filtered sequentially through $0.8 \mu\text{m}$, $0.2 \mu\text{m}$ and $0.015 \mu\text{m}$, during SO298. Total Cr in light green, Cr(VI) in dark green, Cr(III) in blue and Cr(VI)/Cr(III) in yellow.

Further interpretation will also be done with multiple ancillary parameters to investigate further controls on the redox speciation of Cr. This dataset will contribute to an extensive dataset of Cr redox speciation in other OMZs in the Atlantic and Indian Oceans, resulting in a global outlook on Cr redox speciation and how OMZs and various sources affect the speciation of this trace metal.

References

Omanović D & Pižeta I, High Frequency data treatment and visualization with ECDSOFT and OnLineMonitor, 2010.

In Obrador B, Jones ID & Jennings E, NETLAKE toolbox for the analysis of high-frequency data from lakes (Factsheet 5), Technical report (Eds.), NETLAKE COST Action ES1201, pp. 23–27, <http://eprints.dkit.ie/id/eprint/536>.

Pađan J, Marcinek S, Cindrić A, Layglon N, Lenoble V, Salaün P, Garnier C & Omanović D, Improved voltammetric methodology for chromium redox speciation in estuarine waters, *Analytica chimica acta* 2019, 1089, 40–47.

Sander S & Koschinsky A, Onboard-ship redox speciation of chromium in diffuse hydrothermal fluids from the North Fiji Basin, *Marine Chemistry* 2000, 71, 83–102.

Achterberg EP, Steiner Z & Galley CG, South Pacific GEOTRACES, Cruise No. SO289, 18 February 2022 - 08 April 2022, Valparaiso (Chile) – Noumea (New Caledonia), *SONNE-Berichte, Begutachtungspanel Forschungsschiffe*, SO289, 2022, 141 pp, https://doi.org/10.48433/cr_so289.

Achterberg EP, & Singh ND, Equatorial Pacific GEOTRACES, Cruise No. SO298, April 14 - June 2 2023, Guayaquil (Ecuador) – Townsville (Australia), In *SONNE-Berichte* (SO298, pp. 1–106), 2023, *Begutachtungspanel Forschungsschiffe*, https://doi.org/10.48433/cr_so298.

SO289

GEOTRACES GP21, Radiogenic Nd Isotopes and Rare Earth Elements in the South Pacific Ocean

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

Z. Zhang, M. Frank

Radiogenic neodymium isotopes (ϵNd) are widely used to trace modern ocean circulation and to reconstruct past water mass mixing in paleoceanographic archives. Their utility relies on the assumption of quasi-conservative behavior in the open ocean, yet uncertainties remain due to the potential influence of boundary exchange, benthic fluxes, volcanic inputs, or hydrothermal activity. The South Pacific Ocean is a particularly important setting to test these processes: it is the largest ocean basin, contains sluggish overturning circulation, and lies adjacent to extensive volcanic provinces. At the same time, this basin experienced one of the most energetic volcanic events of the past century, the eruption of Hunga Tonga–Hunga Ha’apai (HTHH) in January 2022, which deposited vast amounts of volcanic ash across the South Pacific Gyre. The GEOTRACES GP21 (SO289) expedition, conducted in February–April 2022 along 26–32°S, thus provided an exceptional opportunity to investigate both the transient impact of volcanic inputs on surface ocean biogeochemistry and the long-term conservative behavior of Nd isotopes in intermediate and deep waters.

Surface samples collected during GP21 revealed a distinct volcanic imprint in the western South Pacific Gyre (SPG), in particular in the main ash deposition area identified by a volcanic ash dispersal model, with altered Nd isotopic composition and rare earth element (REE) patterns compared to previous observed values at similar locations. These geochemical anomalies likely extended eastward, consistent with ash dispersal by winds and surface currents. Dissolution of volcanic material was confirmed by a pumice fragment collected during the cruise, which showed isotopic and REE characteristics matching the dissolved signals. Associated trace element measurements documented elevated aluminum (Al), manganese (Mn), and iron (Fe), with Al most strongly correlated to the radiogenic

Nd isotopic shifts, suggesting aluminosilicate dissolution as the primary driver. In contrast, Fe showed signs of rapid removal by scavenging and biological uptake. Chlorophyll-a profiles and satellite observations indicated enhanced biological activity in the euphotic zone, supporting the idea that volcanic Fe and other micronutrient inputs stimulated productivity in this otherwise oligotrophic region. From measured ejecta compositions, we estimate that the eruption delivered ~0.16 kt of Nd and ~32 kt of Fe to the SPG, fluxes comparable to the annual global dust-borne Nd flux and the annual dust-borne Fe flux to the entire SPG, respectively. These results demonstrate that the HTHH eruption produced a rare, basin-scale fertilization event with measurable consequences for surface ocean chemistry and biology.

At depth, GP21 provides a comprehensive test of whether Nd isotopes and concentrations behave conservatively under present circulation. Full-depth Nd isotopes effectively trace major water masses in the South Pacific, with more negative values reflecting water masses from the Southern Ocean and more positive values indicating influences from the North and equatorial Pacific. These measurements, coupled with water mass fractions derived from Optimum Multi-Parameter Analysis, show that both isotopic compositions and concentrations in the interior SPG are consistent with conservative mixing of source waters. Departures from this pattern are limited to the eastern and western boundaries, where exchange with margin sediments imparts more radiogenic signatures. When integrated with other South Pacific zonal sections, a coherent picture emerges in which intermediate and deep waters preserve their source characteristics during transport from the subpolar South Pacific to subtropical latitudes, with only minor alteration along advective pathways. Of particular note, Lower Circumpolar Deep Water retains its distinct unradiogenic Nd isotopic signature while transiting northward to ~20°S, despite flowing adjacent to volcanogenic sediment sources along the Tonga–Kermadec Arc. These results confirm that water mass mixing, rather than benthic input, exerts the dominant control on Nd isotope distributions across the South Pacific interior, while boundary regions function as localized hotspots of isotopic exchange.

Together, the GP21 observations highlight both the resilience and sensitivity of Nd cycling in the South Pacific. On short timescales, episodic volcanic activity can inject trace elements and isotopes in amounts comparable to annual dust fluxes, fertilizing surface waters and leaving measurable geochemical imprints. On longer timescales, however, Nd isotopes and concentrations remain largely conservative along major water mass pathways, reinforcing their value as robust tracers of ocean circulation for paleoceanographic reconstructions. The combined results underscore the need to distinguish between boundary-influenced settings, where non-conservative processes dominate, and the open ocean interior, where conservative behavior prevails.

SO290

Land-ocean interaction in southern New Zealand during the past 200 ka

Authors

Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Marine Geology | Rostock, Germany

H. Krüger, H. W. Arz, J. Kaiser

University Brest, CNRS, Ifremer, Geo-Ocean | Plouzane, France

S. Toucanne

Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research | Bremerhaven, Germany

F. Lamy, L. Lembke-Jene

GFZ Helmholtz Centre for Geosciences | Potsdam, Germany

N. Nowaczyk

Institute for Chemistry and Biology of the Marine Environment (ICBM), Carl von Ossietzky Universität Oldenburg | Oldenburg, Germany

K. Pahnke

During the Late Quaternary global climate variations and interactions with the southern westerly wind belt and the adjacent surface ocean circulation caused glacier advances and retreats in New Zealand's Southern Alps. Most studies in this region, however, focus on the last glacial period and evidence of older glacier activity is more fragmentary. The use of marine sediment cores as continuous archives for glacier fluctuations over glacial-interglacial cycles is a common method to circumvent such terrestrial archive limitations. Our study investigates the glaciation history of New Zealand's South Island over the past 200,000 years and its interaction with paleoceanographic changes of the adjacent Southeast Tasman Sea. Solander Trough south of New Zealand represents a major conduit of terrestrial sediments from the Southern Alps. The trough is narrow (100–130 km) and elongate and begins at ~500 m water depth at 46.5°S extending down to ~4000 m water depth at 51°S by, following a S-SW direction for 550 km (Bostock et al., 2015). Thick sequences of terrigenous and hemipelagic sediments occur in the Solander Trough that were primarily produced by erosion from the Southern

Alps (Schoor et al., 1998). Core SO290-17-1 was recovered from Solander Trough at 47°14.744'S and 165°57.573'E with a piston corer at a water depth of 2248 m and covers 15 meters (see Pahnke et al., this volume; Pahnke et al., 2022).

The stratigraphy of the core is based on radiocarbon dating, oxygen isotopes from benthic foraminifera, and paleo- and rockmagnetic measurements. Furthermore, X-ray fluorescence core scanning data are used for wiggle-matching the last glacial period to a very well-dated neighboring sediment core (TAN1106-28; Toucanne, S. pers. communication, 2025). To investigate changes in sediment source and hence glacier dynamics on land, we use detrital radiogenic neodymium isotopes (expressed as ϵNd) and terrigenous element ratios as proxies for source-specific terrestrial input.

While unradiogenic ϵNd values are likely linked to input from the Southwest Fiordland block, which is composed of felsic rocks (Palaeozoic granite and quartzofeldspathic metasediments with ϵNd values of ~ -5 to -11), the Eastern and Western Fiordland belts (Jurassic-Cretaceous (meta)-igneous rocks) and the East Southland (volcano-sedimentary rocks) represent the more radiogenic intermediate/mafic ϵNd endmember with ϵNd values of -4 to $+5$ (e. g., Pickett & Wasserburg, 1989). Generally, interglacials show more unradiogenic ϵNd values down to -6 . In contrast, less unradiogenic ϵNd values during glacials of up to -2 indicate an eastward glacier expansion. In more detail, the ϵNd data suggests glacier advances also during MIS 5b and 5d, corresponding to a dominance of beech forests from pollen records during these cooler intervals (Lorrey & Bostock, 2017). Furthermore, our data imply large glacier fluctuations during MIS 6 with 3 major expansion phases at ~ 137 ka, ~ 157 ka and ~ 178 ka. This corresponds to the multiple phases of glaciation in MIS 6 as indicated by Rother et al. (2010) from a terrestrial sediment record in the Hope Valley, North Canterbury. The XRF Ti/K record of core SO290-17-1 largely resembles the ϵNd signal showing increased Ti/K values during glacial periods. Higher resolution and variability of this record suggest even more frequent phases of glacier expansions during MIS 3 and 6, which require further investigations. Detailed paleoceanographic data are currently being collected from the same sediment core SO290-17-1 to assess the role of regional surface-ocean properties and the Southern Westerly Winds in shaping the continental climate of southern New Zealand particularly during glacial periods.

References

Bostock HC, Hayward BW, Neil HL, Sabaa AT & Scott GH, Changes in the position of the Subtropical Front south of New Zealand since the last glacial period, *Paleoceanography* 2015, 30(7), 824–844. <https://doi.org/10.1002/2014PA002652>.

Lorrey A & Bostock H, The Climate of New Zealand through the Quaternary (pp. 67–139), In: Shulmeister, J. Landscape and Quaternary Environmental Change in New Zealand, Atlantis Press 2017, https://doi.org/10.2991/978-94-6239-237-3_3.

Pahnke K, Lamy F, & SO290 scientific party, Paleoceanography of the southern Tasman Sea and glaciation history of the South Island, New Zealand (PaläoTaNZ), SONNE-Berichte 2022, pp. 83. doi:10.48433/cr_so290.

Pickett DA & Wasserburg GJ, Neodymium and strontium isotopic characteristics of New Zealand granitoids and related rocks, Contributions to Mineralogy and Petrology 1989, 103(2), 131–142, <https://doi.org/10.1007/BF00378499/METRICS>.

Rother H & Shulmeister J, Synoptic climate change as a driver of late Quaternary glaciations in the mid-latitudes of the Southern Hemisphere, Climate of the Past 2006, 2(1), 11–19, <https://doi.org/10.5194/cp-2-11-2006>.

Schuur CL, Coffin MF, Frohlich C, Massell CG, Karner GD, Ramsay D & Caress DW, Sedimentary regimes at the Macquarie Ridge Complex: Interaction of Southern Ocean circulation and plate boundary bathymetry, Paleoceanography 1998, 13(6), 646–670. <https://doi.org/10.1029/98PA02357>.

SO290

Changes in sea surface temperatures and dust input at the Lord Howe Rise (Tasman Sea) over the past glacial-interglacial cycles

Authors

Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) | Bremerhaven, Germany

F. Lamy, N. Ruggieri, L. Lembke-Jene, M. van der Does

Institute for Chemistry and Biology of the Marine Environment (ICBM), Carl von Ossietzky Universität Oldenburg | Oldenburg, Germany

K. Pahnke, T. Struve

Leibniz Institute for Baltic Sea Research Warnemünde (IOW) | Warnemünde, Germany

H.W. Arz

The Lord Howe Rise, situated west of New Zealand's North Island, lies outside the influence of fluvial terrigenous input from New Zealand and Australia. Consequently, sediment cores from this region are dominated by biogenic (carbonate) components, while minor terrigenous contribution, primarily of aeolian origin. We selected sediment core SO290-33-2 for detailed studies of alkenone-based sea surface temperatures (SST) and dust input over the past several glacial-interglacial cycles.

The stratigraphic framework is based on stable oxygen isotope measurements of benthic foraminifera. Despite the relatively low temporal resolution of the $\delta^{18}\text{O}$ record and its comparatively high variability, nearly all marine isotope stages can be identified back to ~580 ka. Building on this age framework, we further refined the stratigraphy by comparing the XRF core-scanner-based Fe concentration record with the dust concentration record from the EPICA Dome C ice core, correlating glacial maxima. Sedimentation rates derived from this age model range between ~0.5 and 2.2 cm/kyr.

Biomarker time-series

The alkenone-SST record reveals pronounced glacial-interglacial variability over the past ~580 ka. During the Holocene, reconstructed SSTs of ~22.5 °C closely match present-day summer SSTs at the core site (see Ruggieri et al., this volume). By contrast, interglacial SSTs throughout the last 580 ka average ~24 °C. The last interglacial (~125 ka) is marked by peak summer SSTs of up to 25 °C, about 2.5 °C warmer than today. Glacial SSTs in the alkenone record show stronger variability among individual glacials, with minimum values of ~17 °C during Marine Isotope Stage (MIS) 10. Overall, glacial-interglacial amplitudes are relatively large, on the order of 5–6 °C, particularly after the Mid-Brunhes Transition (~MIS 11). This pattern resembles the temperature variability observed in the EPICA Dome C (EDC) ice core. Interestingly, in core SO290-33-2 as in the EDC record, the smaller pre-Mid-Brunhes amplitudes reflect relatively warm glacials, whereas in the ice core, the reduced amplitudes result from cooler interglacials.

A second key biomarker dataset is the concentration of n-alkanes. Here, mass accumulation rates (MAR) of n-alkanes generally peak during glacials and broadly follow the dust concentration record from the EDC ice core. This supports our working hypothesis that plant waxes preserved in the pelagic sediments of the Lord Howe Rise (core SO290-33-2) originate from Australia and were delivered via aeolian transport. This interpretation is consistent with parallel provenance studies on dust at the same coring site (see Pahnke et al., this volume, Warnez et al., this volume).

Lithogenic Input (Australian Dust)

In addition to the n-alkane record, we investigated high-resolution changes in lithogenic content and lithogenic MAR derived from XRF core-scanner data and geochemical calibrations conducted (Figure 1). The data reveal a clear pattern of elevated lithogenic contents and lithogenic MAR during glacial periods. The highest lithogenic values occur during MIS 8 and 10. As in the ice core record, the amplitudes of lithogenic variability are markedly reduced in the older section of the record (pre-Mid-Brunhes).

We compare our MAR datasets (lithogenic content and n-alkanes) with published records from the Subantarctic South Pacific that also reflect dust input from Australia (and, in the Southern Ocean, New Zealand) (Lamy et al., 2014). While interglacial lithogenic MAR in the Tasman Sea is broadly comparable to the Subantarctic South Pacific, glacial maxima show substantial differences. Here, values from SO290-33-2 are clearly lower than those from the Pacific records, particularly when compared with core PS75/76. This core, located in the Southwest Pacific, lies relatively close to Australian (and New Zealand) dust

source regions (Struve et al., 2022). The fact that lithogenic MAR at SO290-33-2 are lower than in the more distal Pacific cores appears counterintuitive. A possible explanation is that the distal Pacific sites integrate dust input from a much larger portion of the Australian source area. In contrast, although core SO290-33-2 lies closer to Australia, it is positioned near the northern margin of the major Australian dust source regions.

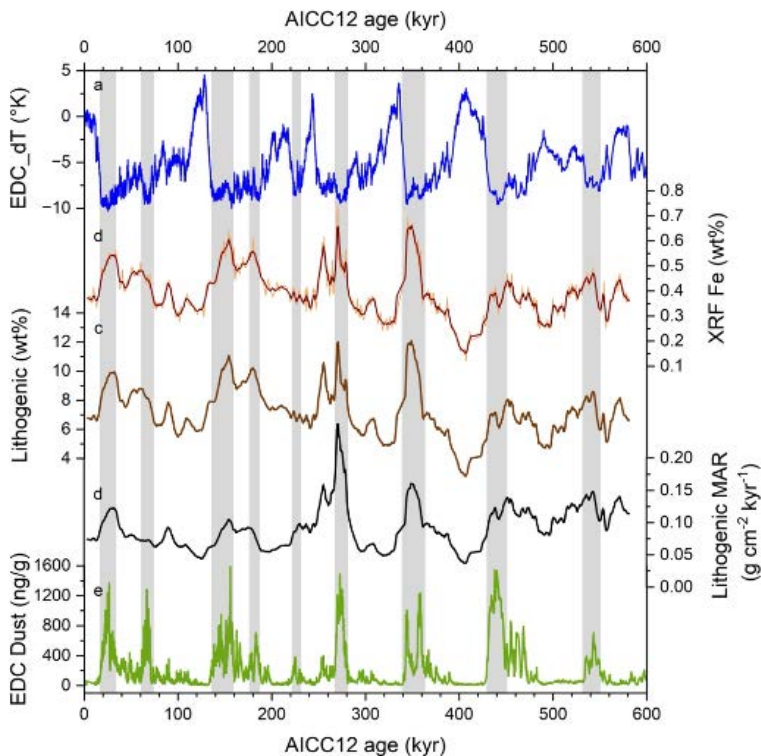


Figure 1: Lithogenic input data from core SO290-33-2. (a) Temperature record from the EPICA Dome C (EDC) ice core (Jouzel et al., 2007). (b) Fe concentrations (XRF core scans). (c) Variations in derived lithogenic content. (d) Lithogenic MAR. (e) Dust concentrations from the EDC ice core (Lambert et al., 2008).

References

Jouzel J, Masson-Delmotte V, Cattani O, Dreyfus G, Falourd S, Hoffmann G, Minster B, Nouet J, Barnola JM, Chappellaz J, Fischer H, Gallet JC, Johnsen S, Leuenberger M, Loulergue L, Luethi D, Oerter H, Parrenin F, Raisbeck G, Raynaud D, Schilt A, Schwander J, Selmo E, Souchez R, Spahni R, Stauffer B, Steffensen JP, Stenni B, Stocker TF, Tison JL, Werner M, Wolff EW, 2007, Orbital and millennial Antarctic climate variability over the past 800,000 years, *Science* 317, 793–796.

Lambert F, Delmonte B, Petit JR, Bigler M, Kaufmann PR, Hutterli MA, Stocker TF, Ruth U, Steffensen JP, Maggi V, Dust-climate couplings over the past 800,000 years from the EPICA Dome C ice core, *Nature* 2008, 452, 616–619.

Lamy F, Gersonde R, Winckler G, Esper O, Jaeschke A, Kuhn G, Ullermann J, Martinez-Garcia A, Lambert F, Kilian R, Increased Dust Deposition in the Pacific Southern Ocean During Glacial Periods, *Science* 2014, 343, 403–407.
doi:10.1126/science.1245424.

Struve T, Pahnke K, Lamy F, Wengler M, Böning P, Winckler G, A circumpolar dust conveyor in the glacial Southern Ocean, *Nature Communications* 2020, 11, 5655,
doi:10.1038/s41467-020-18858-y.

SO290

Bulk properties and biomarker composition of surface sediments from the Tasman Sea

Authors

Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) | Bremerhaven, Germany

N. Ruggieri, F. Lamy, N. Kubik

Institute for Chemistry and Biology of the Marine Environment (ICBM) | Carl von Ossietzky Universität Oldenburg | Oldenburg, Germany

K. Pahnke

The Tasman Sea, spanning mid- to high southern latitudes of the South Pacific, is a key region for the formation and northward transport of Antarctic intermediate and bottom waters, thereby influencing global ocean circulation and climate. During SONNE cruise SO290, water samples and sediment cores were collected along latitudinal and eastward transects off New Zealand. Surface sediments recovered with a multicorer provide essential baseline data to refine regional proxy interpretations for paleoenvironmental reconstructions. Here, we focus on bulk sediment properties (e. g., carbonate and opal content, grain size), two independent organic proxies for sea surface temperature (SST) reconstructions, based on alkenone and glycerol dialkyl glycerol tetraether (GDGT), and plant wax n-alkanes as indicators of terrigenous input.

Bulk Sediment Parameters and n-Alkanes

The sediments off New Zealand are dominated by terrigenous material and biogenic carbonate (Figure 1). In the southern sector off the South Island, strong fluvial input results in markedly lower CaCO_3 contents (ca. 10–30%). Sediment cores from this area record the highest sedimentation rates, indicating that the reduced CaCO_3 levels are primarily due to dilution by terrigenous material. Further north, towards the pelagic Tasman Sea, CaCO_3 contents increase substantially and reach values exceeding 90% on the Lord Howe Rise. The low terrigenous fraction in this region likely reflects aeolian input from Australia (see description of

core SO290-33-2). Opal concentrations in surface sediments are generally low and rarely exceed 5%, even off the southern tip of New Zealand (Figure 1).

The distribution of n-alkane concentrations (Figure 1) closely follows the pattern of terrigenous input. Consistent with earlier studies off the east coast of New Zealand (Jaeschke et al., 2017), we infer that plant waxes were mainly supplied by fluvial transport, most likely derived from the dense coastal vegetation belt of the New Zealand Alps. Further offshore, an additional contribution from aeolian transport originating in Australia is probable.

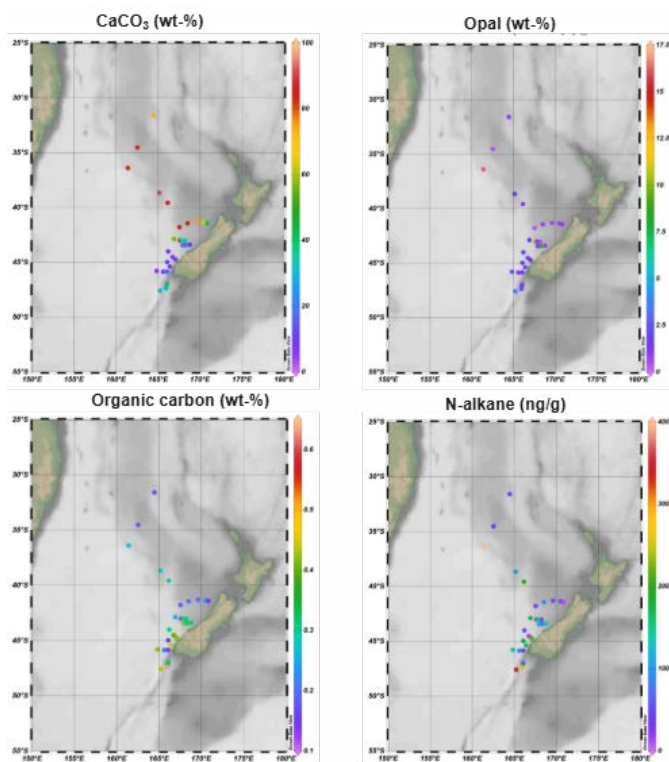


Figure 1: Bulk sediment parameters and n-Alkanes measured in surface sediments from cruise SO290.

Sea Surface Temperature

We analyzed several biomarker proxies for SST reconstructions in our set of surface sediments, with a primary focus on alkenone-based $U^{K'}_{37}$ SST. Figure 2 compares the alkenone-derived SSTs, calculated using the surface sediment calibration of Müller et al. (1998), with modern annual mean and seasonal instrumental SSTs. The results show that alkenone-SSTs are clearly higher than modern annual mean temperatures and most closely reflect warm austral summer

conditions. This seasonal bias of alkenone-SSTs is consistent with findings from the Subantarctic Southern Ocean (Jaeschke et al., 2017; Sikes et al., 1997). Our data demonstrate that in the Tasman Sea, extending into the subtropics, alkenone-SSTs predominantly record summer temperatures.

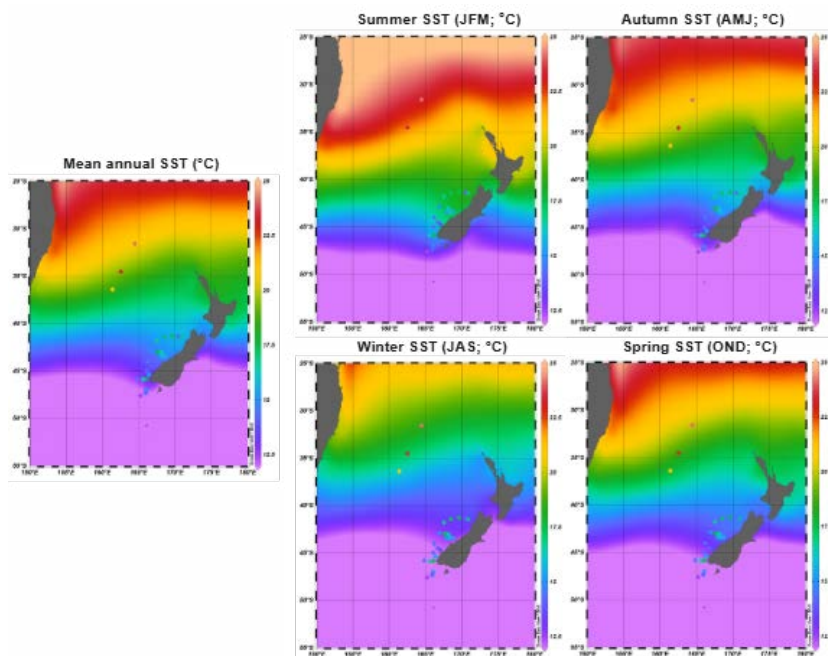


Figure 2: Alkenone-based SST reconstructed from surface sediments (calculated following Müller et al., 1998) compared with annual mean and seasonal SSTs (WOA05; Locarnini et al., 2006).

In addition to alkenone-based reconstructions, we tested other biomarker proxies based on glycerol dialkyl glycerol tetraethers (GDGTs; Figure 3). The TEX₈₆ index consistently yielded SSTs that are substantially warmer than modern summer values, a pattern also reported from other oceanic regions (e. g., Kim et al., 2010; Ho et al., 2014), except at the more northerly stations on the Lord Howe Rise, situated west of New Zealand's North Island, where the reconstructed temperatures are in good agreement with modern summer SSTs. By contrast, the SST RI-OH index (Lü et al., 2015) provides a closer match to modern summer SSTs, particularly in the Tasman Sea off New Zealand. On the Lord Howe Rise, however, the RI-OH-derived SSTs appear colder than observed (Figure 3).

Together, these results highlight spatial heterogeneity in proxy performance and provide a framework for improved paleoceanographic reconstructions in the Tasman Sea.

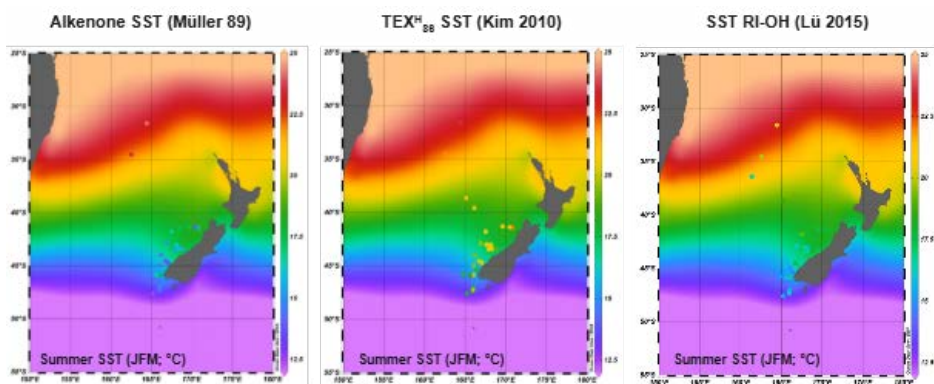


Figure 3: Comparison of reconstructed SSTs using different biomarker proxies. Alkenone SST calculated following Müller et al. (1998); TEX₈₆ following Kim et al. (2010); SST RI-OH following Lü et al. (2015).”

References

- Ho SL, Mollenhauer G, Fietz S, Martinez-Garcia A, Lamy F, Rueda G, Schipper K, Meheust M, Rosell-Mele A, Stein R & Tiedemann R, Appraisal of TEX₈₆ and TEX_{86L} thermometries in subpolar and polar regions, *Geochimica Et Cosmochimica Acta* 2014, 131, 213–226; 10.1016/j.gca.2014.01.001.
- Jaeschke A, Wengler M, Hefter J, Ronge TA, Geibert W, Mollenhauer G, Gersonde R & Lamy F, A biomarker perspective on dust, productivity, and sea surface temperature in the Pacific sector of the Southern Ocean, *Geochimica Et Cosmochimica Acta* 2014, 204, 120–139; 10.1016/j.gca.2017.01.045.
- Kim JH, van der Meer J, Schouten S, Helmke P, Willmott V, Sangiorgi F, Koc N, Hopmans EC & Damste JSS, New indices and calibrations derived from the distribution of crenarchaeal isoprenoid tetraether lipids: Implications for past sea surface temperature reconstructions, *Geochimica Et Cosmochimica Acta* 2010, 74(16), 4639–4654; 10.1016/j.gca.2010.05.027.
- Locarnini RA, Mishonov AV, Antonov JI, Boyer TP & Garcia HE, *World Ocean Atlas 2005, Volume 1: Temperature*, In: U.S.G.P. Office (Editor). Levitus S, Ed. NOAA Atlas NESDIS 61 2006, Washington, D.C., 182 pp.
- Lü X, Liu X-L, Elling FJ, Yang H, Xie S, Song J, Li X, Yuan H, Li N & Hinrichs K-U, Hydroxylated isoprenoid GDGTs in Chinese coastal seas and their potential as a paleotemperature proxy for mid-to-low latitude marginal seas, *Organic Geochemistry* 2015, 89–90, 31–43; 10.1016/j.orggeochem.2015.10.004.

Müller PJ, Kirst G, Ruhland G, von Storch I & Rosell-Melé A, Calibration of the alkenone paleotemperature index U37K' based on core-tops from the eastern South Atlantic and the global ocean (60°N–60°S), *Geochimica et Cosmochimica Acta* 1998, 62(10), 1757–1772; 10.1016/s0016-7037(98)00097-0.

Sikes EL, Volkman JK, Robertson LG & Pichon JJ, Alkenones and alkenes in surface waters and sediments of the Southern Ocean: Implications for paleotemperature estimation in polar regions, *Geochimica Et Cosmochimica Acta* 1997, 61(7), 1495–1505; 10.1016/S0016-7037(97)00017-3.

SO290

Dust provenance in the Tasman Sea over the past 140,000 years

Authors

Institute for Chemistry and Biology of the Marine Environment (ICBM), Carl von Ossietzky Universität Oldenburg | Oldenburg, Germany

J. Warnatz, T. Struve, K. Pahnke

Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) | Bremerhaven, Germany

F. Lamy

Atmospheric mineral dust influences Earth's radiation budget, cloud formation, precipitation, atmospheric chemistry, surface albedo and nutrient supply to terrestrial and marine ecosystems. Dust-derived iron (Fe) input to the Fe-deficient Southern Ocean during glacial periods was hypothesised to have enhanced primary productivity and therefore carbon sequestration, contributing to the glacial drawdown of atmospheric CO₂ (Martin et al., 1990). Dust provenance can provide valuable information on the dust-climate feedback in the Southern Hemisphere, but the interpretation strongly depends on the available information about Potential Source Areas (PSA). Australia is the major dust supplier to the South Pacific today (Prospero et al., 2002; Wengler et al., 2019; Struve et al., 2020) and hosts multiple PSAs. Sediments in the Tasman Sea, particularly on bathymetric highs like the Lord Howe Rise that are separated from river input from New Zealand and Australia, have the potential to record past Australian dust export and its geochemical fingerprint. Here we present radiogenic neodymium (Nd), lead (Pb) and strontium (Sr) isotope compositions along with rare earth element (REE) data of the lithogenic dust fraction (<5 µm) of 24 sediment samples from core SO290-33-2 in the northern Tasman Sea spanning the last ~140 ka BP (Figure 1).

The REE composition confirms complete removal of any authigenic phases in the dust samples, validating the lithogenic source of the leached fine fraction. The radiogenic isotope results show surprisingly high radiogenic Pb signatures of 19.03 ± 0.02 for $^{206}\text{Pb}/^{204}\text{Pb}$ in combination with unradiogenic Nd isotope compositions (expressed in ϵNd notation) of -6.6 ± 0.3 . Significant correlation

between the different Pb isotopes and ϵNd ($0.68 \leq R^2 \leq 0.85$) indicates the mixing of dust from two major PSAs, one with radiogenic ϵNd and unradiogenic $^{206}\text{Pb}/^{204}\text{Pb}$, and the other with a less radiogenic ϵNd and radiogenic $^{206}\text{Pb}/^{204}\text{Pb}$.

Compared to existing PSA data, one source can be clearly attributed to the Lake Eyre Basin (Australia), possibly with a small admixture of dust from the Darling Basin (Australia). This is consistent with previous studies that have identified Lake Eyre and the Darling Basin as the main sources of dust in Holocene sediments from the South Pacific (Struve et al., 2020; Wengler et al., 2019). The second source, with more unradiogenic Nd and radiogenic Pb isotopes, cannot be clearly identified on the basis of published PSA data. A contribution from dust from Namibia, Murray Basin (Australia), Western Australia, and the North Island of New Zealand can be ruled out geochemically. A significant contribution from the South Island of New Zealand can also be ruled out due to the geographic location of SO290-33-2 northwest of New Zealand and thus against prevailing westerly winds.

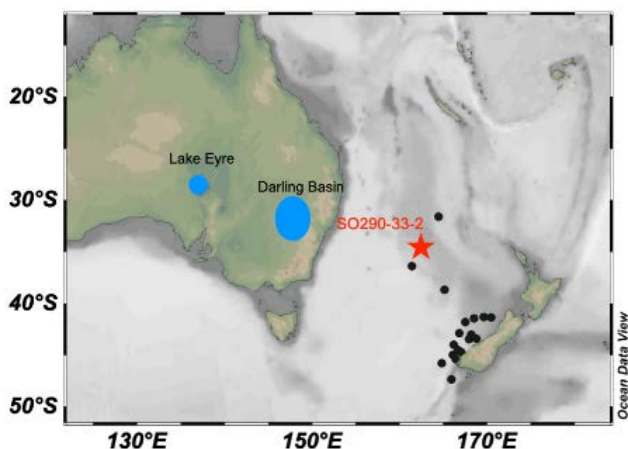


Figure 1: Location of sediment core SO290-33-2 (red star) on Lord Howe Rise in the Tasman Sea together with other stations of cruise SO290 (black circles). Blue symbols mark important dust source areas in Australia. Map generated using Ocean Data View (Schlitzer, 2025).

Central and southern South America ($24\text{--}32^\circ\text{S}$ and $>32^\circ\text{S}$) are important sources of dust for the South Atlantic and have also been detected in Antarctic ice cores (Barkley et al., 2024; Delmonte et al., 2004). South American dust from $24\text{--}32^\circ\text{S}$ dominates in the central South Pacific (Struve et al., 2022). The Pb isotopes of South American dust from $24\text{--}32^\circ\text{S}$ show less radiogenic values than the samples from SO290-33-2 and could therefore be considered a second source of dust. However, the Nd isotopes of this PSA are more radiogenic than the samples from Lord Howe Rise, which is inconsistent with the less radiogenic Nd composition of the second dust source. The second endmember of the lithogenic dust in

SO290-33-2 can therefore not be identified without additional PSA data. However, the data provide an important basis for characterizing the origin of dust in marine sediments and its changes in the course of past climate fluctuations.

The temporal variations in dust provenance along the sediment core over the last 140 ka show increased Lake Eyre influence at the transitions between isotope stages without clearly tracing the glacial-interglacial cycles. Instead, changes in Nd and Pb isotope ratios (and in some cases Sr isotopes) coincide with fluvial activity and changes in water levels in the Lake Eyre Basin (Cohen et al., 2022; Cohen et al., 2015). During reduced fluvial activity, the Lake Eyre Basin source dominated in SO290-33-2, and during periods of increased fluvial activity, the dust origin shifted to the second, undefined dust source. The increasingly arid conditions from Marine Isotope Stage (MIS) 5 to the Last Glacial Maximum (MIS2) are reflected in the iron concentrations in SO290-33-2, which can be used as an indicator of dust quantity (see Pahnke et al., this volume). Changes in fluvial activity and thus moisture in the Lake Eyre Basin have been linked primarily to changes in the Indo-Australian summer monsoon (Cohen et al., 2022). The switch to the second dust source during humid conditions in the Lake Eyre Basin suggests that the second dust source is located in southern Australia, which is not influenced by the Indo-Australian summer monsoon, but primarily by winter-dominated precipitation associated with the southern westerly winds (e. g., Gingele et al., 2007). The marked shift towards dominance of the Lake Eyre dust source from the last glacial period to the Holocene can be explained by the fact that the Indo-Australian summer monsoon did not penetrate inland Australia during the Holocene, as it did in the preceding period (Cohen et al., 2015).

References

- Barkley AE, Winckler G, Recasens C, Kaplan MR, Koffman BG, Calabozo F, Middleton JL, Anderson RF, Cai Y, Bolge L, Longman J, Goldstein SL, Patagonian dust, Agulhas Current, and Antarctic ice-rafted debris contributions to the South Atlantic Ocean over the past 150,000 years, *Proceedings of the National Academy of Sciences* 2024, 121, e2402120121, doi:10.1073/pnas.2402120121.
- Cohen TJ, Jansen JD, Gliganic LA, Larsen JR, Nanson GC, May J-H, Jones BG, Price DM, Hydrological transformation coincided with megafaunal extinction in central Australia, *Geology* 2015, 43, 195–198, doi:10.1130/G363461.
- Cohen TJ, Arnold LJ, Gázquez F, May J-H, Marx SK, Jankowski NR, Chivas AR, García A, Cadd H, Parker AG, Jansen JD, Fu X, Waldmann N, Nanson GC, Jones BG, Gadd P, Late Quaternary climate change in Australia's arid interior: Evidence from Kati Thanda – Lake Eyre, *Quaternary Science Reviews* 2022, 292, 107635, doi:10.1016/j.quascirev.2022.107635.

Delmonte B, Basile-Doelsch I, Petit J R, Maggi V, Revel-Rolland M, Michard A, Jagoutz E, & Grousset F, Comparing the EPICA and Vostok dust records during the last 220,000 years: stratigraphical correlation and provenance in glacial periods, *Earth-Science Reviews* 2004, 66(1–2), 63–87, doi:10.1016/j.earscirev.2003.10.004.

Gingele F, De Deckker P, Norman M, Late Pleistocene and Holocene climate of SE Australia reconstructed from dust and river loads deposited offshore the River Murray Mouth, *Earth and Planetary Science Letters* 2007, 255, 257–272.

Martin JH, Glacial-interglacial CO₂ change: the iron hypothesis, *Paleoceanography* 1990, 5, 1–13, doi:10.1029/PA005i001p00001.

Prospero JM, Ginoux P, Torres O, Nicholson SE, Gill TE, Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, *Reviews of Geophysics* 2002, 40, 1002, doi:10.1029/2000RG000095.

Schlitzer R, Ocean Data View, <https://odv.awi.de> 2025.

Shoenfelt EM, Winckler G, Lamy F, Anderson RF, Bostick BC, Highly bioavailable dust-borne iron delivered to the Southern Ocean during glacial periods, *Proceedings of the National Academy of Sciences*, 2018, 115, 11180, doi:10.1073/pnas1809755115.

Struve T, Pahnke K, Lamy F, Wengler M, Böning P, Winckler G, A circumpolar dust conveyor in the glacial Southern Ocean, *Nature Communications* 2020, 11, 5655, doi:10.1038/s41467-020-18858-y.

Struve T, Longman J, Zander M, Lamy F, Winckler G, Pahnke K, Systematic changes in circumpolar dust transport to the Subantarctic Pacific Ocean over the last two glacial cycles, *Proceedings of the National Academy of Sciences* 2022, 119, e2206085119, doi:10.1073/pnas2206085119.

Wengler M, Lamy F, Struve T, Borunda A, Böning P, Geibert W, Kuhn G, Pahnke K, Roberts J, Tiedemann R, Winckler G, A geochemical approach to reconstruct modern dust fluxes and sources to the South Pacific, *Geochimica et Cosmochimica Acta* 2019, 264, 205–223, doi:10.1016/j.jgca.2019.08.02.

SO293

AleutBio – Aleutian Trench Biodiversity Studies

Authors

Senckenberg Research Institute | Frankfurt am Main, Germany

S. Kaiser, D. Di Franco, A. Kelch, A. Brandt

University of Lodz | Lodz, Poland

S. Kaiser (present address)

Geosphere Austria | Vienna, Austria

D. Di Franco (present address)

The AleutBio expedition (SO293; R/V Sonne, 24 July–6 September 2022) implemented a coordinated, spatially explicit biodiversity survey across biological size classes (from protists to megafauna) in the eastern Bering Sea and the Aleutian Trench (abyssal to hadal depths). The overarching objective was to produce an integrated baseline of species diversity, community structure, evolutionary history and biogeographic connectivity for a tectonically complex and climatically sensitive region that bridges the North Pacific and Arctic gateways. Sampling targeted a depth-stratified series of stations and combined benthic quantitative gear, epibenthic sledges, imagery, and targeted collections to maximise taxonomic coverage and preserve material for morphological, molecular and biochemical analyses (Brandt 2022).

Here we use deep-sea isopod crustaceans as an exemplar taxon to illustrate outcomes from an integrative, multi-evidence framework. Individual specimens were subjected to detailed morphological examination, DNA barcoding of the mitochondrial cytochrome c oxidase subunit I (COI), targeted sequencing of complete mitogenomes where material and DNA quality permitted, selected nuclear markers (e. g., 18S), and proteomic profiling (matrix-assisted laser desorption/ionization time-of-flight mass spectrometry, MALDI-TOF) to acquire concordant character sets for species delimitation and unravel phylogenies. These datasets were analysed with complementary approaches: sequence-based operational taxonomic unit (OTU) delineation, species delimitation models, haplotype network and phylogeographic inference, and tree-based phylogenetics calibrated by mitogenomic and nuclear signal. By integrating independent lines

of evidence we generated robust species hypotheses, detected morphologically cryptic lineages, quantified richness across depth strata, and inferred patterns of population connectedness and structure for downstream biogeographic synthesis. The use of COI as a rapid discriminator follows the established DNA-barcoding framework, while mitogenomes and nuclear markers provided increased phylogenetic signal for resolving deeper systematic nodes. Proteomic fingerprints (MALDI-TOF) were applied as an additional, rapid cross-validation tool increasingly demonstrated in arthropod taxonomy (e. g. Rossel et al., 2024).

Key results include (1) discovery of numerous species not matching any described taxa, including several deeply divergent mitochondrial lineages that were concordant with morphological or proteomic differentiation; (2) evidence of clear biogeographic affinity between faunas sampled in the Aleutian–Bering region and previously sampled stations in the adjacent Kuril–Kamchatka Trench, supporting faunal exchange across the northwestern Pacific; but also (3) strong signals of dispersal limitation and genetic structuring associated with bathymetric (abyssal vs. hadal), and topographic barriers (Aleutian Ridge) alongside distance, which together appear to restrict gene flow between basins at both shallow abyssal and hadal depths. The prominence of cryptic diversity in isopods mirrors broader patterns documented for marine taxa, underscoring the importance of multi-marker and multi-evidence approaches for accurate richness estimates (e. g. Bickford et al., 2007).

Targeted phylogenomic and mitogenomic analyses of selected clades resolved previously ambiguous systematic relationships and provided molecular support for the recognition of several novel genera-level lineages. These outcomes demonstrate how combined morphological, mitogenomic and nuclear evidence can underpin rigorous taxonomic revision and stable classification in highly diverse groups. Integrative taxonomy – the explicit combination of multiple independent character systems – thus proved essential for delimiting species and higher taxa in a deep-sea context (cf. Dayrat 2005)

Beyond systematics, the results have direct biogeographic and conservation relevance. The spatially explicit patterns of diversity and connectivity established by AleutBio form a necessary baseline to detect future changes in assemblage composition and range shifts driven by climate change, anthropogenic disturbance, and altered oceanographic regimes. Because the deep North Pacific harbours unique and diverse biological communities, high-resolution taxonomic, genetic and spatial data are essential for evaluating species vulnerability, testing hypotheses about dispersal and adaptation, and prioritising targeted research and long-term monitoring. These conclusions align with broader syntheses emphasizing the distinctiveness and sensitivity of deep-sea ecosystems and the urgent need for comprehensive documentation in the face of increasing human impacts (e. g. Ramirez-Llodra et al., 2010)

In summary, the AleutBio integrative program demonstrates that dense, depth-stratified sampling combined with concordant morphological, mitochondrial, nuclear and proteomic datasets produces robust species hypotheses, reveals hidden diversity, clarifies systematics, and maps fine-scale connectivity patterns in previously understudied abyssal–hadal seascapes. These data provide a durable foundation for taxonomic revision, comparative biogeography across the North Pacific–Arctic gateway, and evidence-based conservation planning under ongoing global climate change.

References

Bickford D, Lohman DJ, Sodhi NS, Ng PK, Meier R, et al., Cryptic species as a window on diversity and conservation, *Trends in Ecology & Evolution* 2007, 22(3), 148–155.

Brandt A, SO293 AleutBio (Aleutian Trench Biodiversity Studies) Cruise Report/ Fahrtbericht Cruise No. SO293 24.07.2022–06.09.2022 Dutch Harbor (USA) – Vancouver (Canada) ALEUTBIO (Aleutian Trench Biodiversity Studies), 2022, 209 pages, ISSN: 2510-764X; http://doi.org/10.48433/cr_so293, Database provider: Technische Informationsbibliothek (TIB), TIB-Portal URL: <https://www.tib.eu/de/suchen/id/awi%3A2e09a2d10868cda723395545e3fcc6a29cfb49a8>.

Dayrat B, Towards integrative taxonomy, *Biological Journal of the Linnean Society* 2005, 407–417.

Ramirez-Llodra E, Tyler PA, Baker MC, et al., Deep, diverse and definitely different: unique attributes of the world’s largest ecosystem, *Biogeosciences* 2010, 7(9), 2851–2899.

Rossel S, Peters J, Charzinski N, Eichsteller A, Laakmann S, et al., A universal tool for marine metazoan species identification: towards best practices in proteomic fingerprinting, *Scientific Reports* 2024, 14(1), 1280.

SO294

GEOMAR's Contribution to Deep-Sea Ecosystem Discovery and Management

Authors

Institute of Ocean Sciences, Fisheries and Oceans Canada | Sidney, BC, Canada

C. Du Preez, H. Gartner, D. Labbé

Geological Survey of Canada – Pacific | Sidney, B.C., Canada

K.L. Douglas

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

M. Riedel

The recent GEOMAR-led SO294 expedition to the northern Cascadia Margin has significantly advanced the understanding and management of deep-sea ecosystems by uncovering previously undocumented cold seep habitats along the Canada's Pacific margin. Cold seeps are geochemically active zones in the seafloor where hydrocarbon-rich fluids (primarily methane) bubble out of the seafloor. Cold seep ecosystems in Pacific Canada have historically been overlooked, but a significant shift occurred in 2018 when they were formally recognized as Ecologically and Biologically Significant Areas (EBSAs; DFO 2018). Within increased interest and research, this cold seep area is now under consideration for further management and conservation by Canadian and Indigenous governments in alignment with the commitments made to the United Nations Ocean Decade and the target of achieving 30% ocean protection by 2030.

Through the collection of high-resolution bathymetry and water column data, the GEOMAR-led SO294 expedition identified promising indicators of active cold seeps, significantly increasing the observations of gas plumes in the area (Figure 1). These discoveries catalyzed targeted dives with a remotely operated vehicle (ROV; Canadian Scientific Submersible Facility ROPOS) during a NorthEast Pacific Deep-Sea Exploration Project (NEPDEP) expedition in 2023 by Canadian and coastal First Nations scientists. NEPDEP is a United Nations Ocean Decade endorsed project that contributes to our global understanding of the deep sea through the Challenger 150 program. This particular NEPDEP expedition set out to document the sites of active gas venting as well as their associated ecological communities and benthic structures.

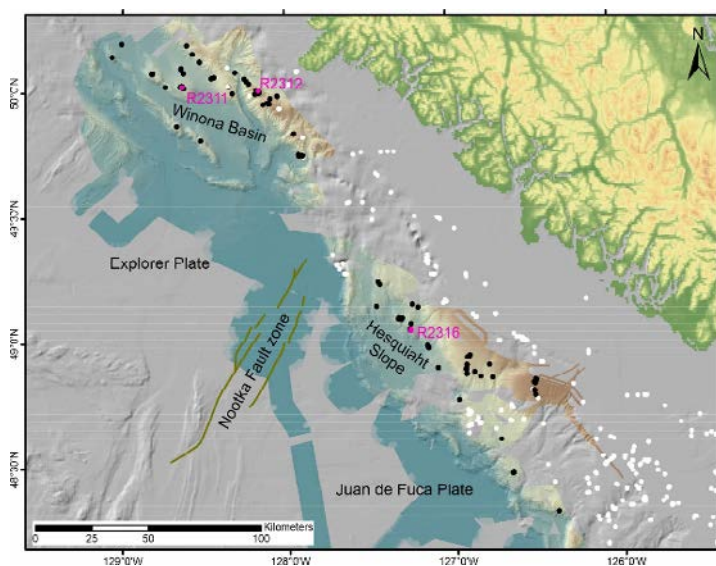


Figure 1: Map with updated multibeam and mapped gas plumes detected off Vancouver Island (white: Riedel et al., 2018; black: newly mapped by SO294). Two locations with prominent gas seeps in the Winona Basin and on the Hesquiaht Slope were investigated with the ROV ROPOS in 2023.

The ROV dives conducted have led to the discovery of diverse cold seep ecosystems that include extensive carbonate ridges (Figure 2) and massive gas hydrate mounds (Figure 3). Visual exploration of the sites at two of the most significant gas plume signatures (visible in echosounder almost to the surface) found extensive bathymetric features and gas hydrates on the seabed (Figure 3).



Figure 2: Example imagery of the extensive carbonate ridge (at least 500m high by 25 km long) and its inhabitants along the Winona Ridge.

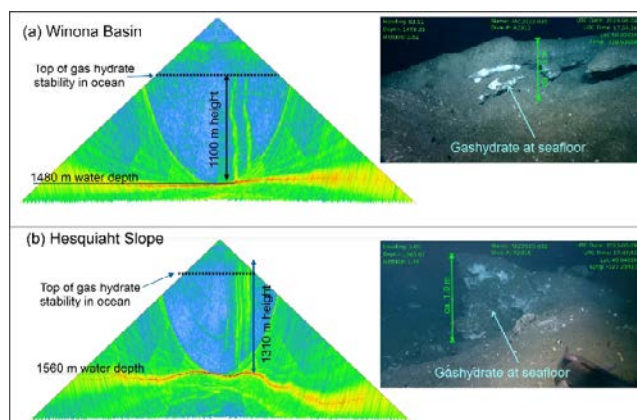


Figure 3: Two significant sites showing water column acoustic data from the echosounder (EM122; left) and ROV ROPOS images of the gas hydrate deposits on the seabed (right). a) Winona Basin, dive R2311 and b) Hesquiaht Slope, dive R2316.

The visual surveys additionally documented the fauna of the area – including chemosynthetic organisms, commercially and culturally significant species of fish and crabs, as well as many ‘background’ associated animals (e. g. Figure 2). An engaging example of cold seeps associated animals occurred at the Hesquiaht Slope cold seeps, where a Deep-Sea Octopus (*Graneledone pacifica*) nursery ground was discovered. These deep-sea mothers were using the carbonate rock boulder field for the attachment and protection of their eggs (Figure 4) – whose gestation period is known to last over 4.5 years (Robinson et al., 2014). One mother was observed fending off Shortspine King Crabs (*Paralomis multispina*; Figure 4c), captivating audiences and bridging the gap between people and the ocean’s depths, becoming an internet sensation while showcasing the indirect ecosystem services provided by cold seeps.



Figure 4: Deep-Sea Octopus Nursery (*Graneledone pacifica*) observed at Hesquiaht Slopes a) three mother in view on carbonate boulder, b) egg attachment and care on a carbonate boulder and c) protection provided to these eggs over 4.5 years.

This collaboration between the GEOMAR-led SO294 expedition and scientists with members of the NEPDEP expedition (included Indigenous and Canadian governments) has led to the identification of key ecosystem services provided by these cold seeps, including their role in deep-sea primary production (chemosynthesis), essential fish habitat for commercial species, nursery grounds for Deep-Sea Octopuses, and stable hard substrates that support diverse communities of deep-sea species including corals and sponges. Additionally, the extensive carbonate features and gas hydrates observed has implications for better understanding deep-sea carbon storage in these cold seep habitats: i) the large carbonate features are formed as the action by the anaerobic oxidation of the venting methane gas precipitates the authigenic carbonate rocks over thousands of years, and ii) the large gas hydrates represent a massive reservoir of carbon built under pressure and cold temperatures. Both these processes are vulnerable to anthropogenic activities such as bottom contact fishing and the warming waters of climate change. The ROV imagery revealed widespread fishing impacts and derelict fishing gear in these areas, underscoring both the ecological vulnerability of cold seeps and their complex interactions with human activities on the seafloor.

Overall, the GEOMAR expedition provided foundational data that has directly contributed to Canadian and First Nations marine conservation science, informed policy decisions, and strengthened stewardship of these vital ecosystems.

References

DFO (Fisheries and Oceans Canada), Assessment of Canadian Pacific Cold Seeps against Criteria for Determining Ecologically and Biologically Significant Areas, DFO Can. Sci. Advis. Sec. Sci. Resp. 2018/002.

Robison B, Seibel B & Drazen J, Deep-Sea Octopus (*Graneledone boreopacifica*) Conducts the Longest-Known Egg-Brooding Period of Any Animal, PLoS ONE 2014, 9(7), e103437, <https://doi.org/10.1371/journal.pone.0103437>.

SO294

Preliminary Interpretation of a Magnetotelluric Profile across the Juan de Fuca Subduction Zone, Results from SO294 CLOCKS.

Authors

GEOMAR Helmholtz Centre for Ocean Research | Kiel, Germany

K. Reeck, G. Franz, M. Riedel, M. Jegen

University of Alberta | Edmonton, Canada

M. Unsworth

Geological Survey of Sidney, Canada | Canada

K. Wang, J. He

University of Hawai'i | Honolulu, USA

A. Haroon

Introduction

The Cascadia margin off western North America has drawn significant scientific interest for more than 4 decades. It is considered as thermal endmember of subduction zones, characterized by the consumption of the young and therefore hot Juan de Fuca (JdF) plate beneath the North American plate at a rate of 35–38 mm/yr. The region is known for its periodical state of locking between the plates, that results in the accumulation of stress, eventually released by elastic rebounding. The resulting megathrust earthquakes occur on average every 500–600 years with the last known major event of magnitude 8.7–9.2 witnessed in 1700 and a tsunami hitting the American west coast and Japan. Since then, the lack of crust or intraplate seismicity suggests that the subduction interface is fully locked. Based on the average subduction rate, a slip deficit of about 15 m has likely been accumulated which infers a great risk for the highly populated North-Pacific coast. As rheology and structure in this area is heavily affected by fluid release and melt generation by the lowering of the solidus temperature, a major

influence on these events is attributed to variations in dehydration of the slab by different mechanisms in various depths. The SO294 CLOCKS cruise aimed at unveiling the state of locking of the megathrust. An amphibious magnetotellurics (MT) survey investigated the deeper structure of the subducting JdF and overlying North American plate to identify free fluid accumulations indicative for dehydration processes. During the cruise we deployed 18 ocean-bottom magnetotelluric (OBMT) stations with a 2.5 nm spacing on a marine, southwest-northeast profile almost perpendicular to the coastline off Vancouver Island (VI). The profile continued onshore VI with 27 MT stations installed by the University of Alberta. At a later stage we included additional data from the previous LITHOPROBE survey to extend the profile across the Strait of Georgia and beyond the coastline of mainland Canada. Together, these datasets provide a comprehensive image of the subduction zone down to a depth of approximately 80 km from the trench along a ~200 km-long profile landwards.

Data Acquisition and Data inversion

All MT data were processed into impedance tensors as a function of frequency. The marine data primarily capture lower frequency signals due to attenuation of high-frequency natural electromagnetic fields by the ocean, which allows deeper penetration into the crust and upper mantle, yet less resolution of shallow features. Although data were acquired along a nominally 2D corridor, we conducted a full 3D inversion to account for complex geological and bathymetric variations that significantly affect MT responses at depth.

The 3D resistivity model of the Juan de Fuca (JdF) subduction zone was generated using a 3D MT inversion algorithm (Avdeeva et al., 2012; Moorkamp et al., 2010), which enables flexible positioning of MT sites on the seafloor and includes bathymetric effects and the marine and Vancouver Island MT data (extended inversion with MT data from continent is ongoing). Bathymetry was incorporated via a rectilinear mesh with constant horizontal cell spacing across the entire inversion volume. We tested a range of initial and background models, and the best fit (RMS misfit of 2.0) was achieved using a starting model that incorporates bathymetry, sedimentary cover from the GlobSed database (Straume et al., 2019), and a prescribed subducting plate geometry. Figure 1 presents a coast-perpendicular vertical section through the preferred inversion model, illustrating the resolved resistivity structure along the profile.

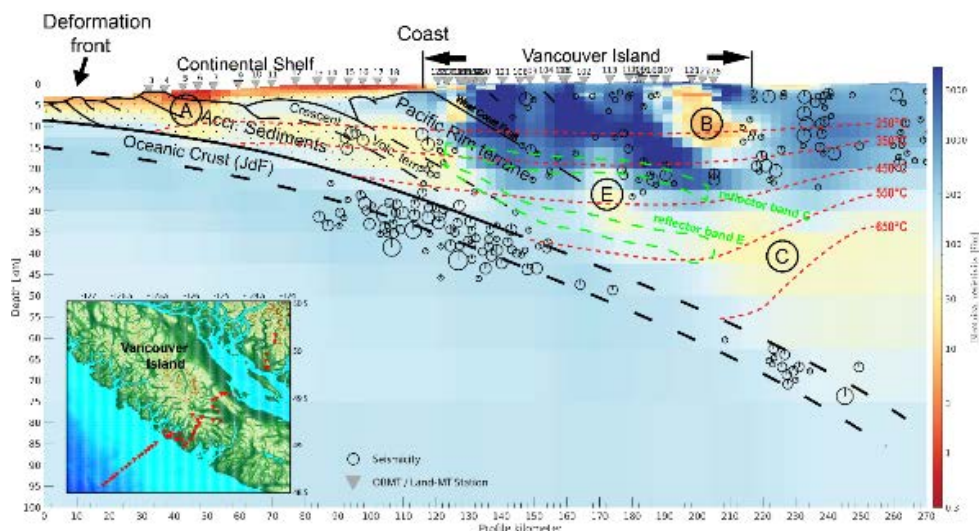


Figure 1: Preferred inversion model (RMS misfit of 2). Overlain on the resistivity model are terrane interpretation, seismicity and location of reflective bands E and C derived after Hyndman et al., 1990. Included isotherms modelled by Gao & Wang (2017).

Offshore, the accretionary wedge is imaged as a low-resistivity anomaly (A), interpreted to reflect fluid-rich sediments undergoing dehydration by compaction and mineral dehydration. Downdip of this conductor, seismicity is observed, consistent with the established link between fluid release and earthquake generation. Notably, while resistivity contrasts between the accretionary complex and the Crescent volcanic terrane are subtle, the older Pacific Rim terrane exhibits higher resistivity. The most resistive feature in the crust corresponds to the Wrangellia Terrane forming the core of Vancouver Island.

Lateral resistivity contrasts between terranes within Vancouver Island diminish below depths of ~22–23 km, suggesting that the terranes are underlain by a different geological unit. The Wrangellia terrane is flanked by two vertical conductive zones extending from the surface to depths of 10–15 km. The western conductor aligns with the West Coast Fault, while the broader and deeper eastern anomaly (B) may be associated with up-thrusted Upper Cretaceous sediments and mudstones of the Nanaimo Group. East of Vancouver Island, the British Columbia mainland crust is predominantly resistive. Conductive anomaly C, situated at greater depth just beyond our data profile, is only marginally resolved by our data and currently analyzed in more detail by adding the LITHOPROBE data.

A key feature in the model is conductive anomaly E, located within the overriding plate above a seismically quiet region of the subducting slab. This anomaly lies between the E- and C-reflective seismic bands (Yorath et al., 1985; Green et al., 1986; Clowes et al., 1987), which have been widely interpreted as zones of fluid

accumulation requiring an elevated porosity (Hyndman et al., 1990). The ABCS profile of Soyer and Unsworth (2006), located parallelly with about 60 km south-eastern offset, imaged this conductor closer to the slabs' top and with a larger vertical extent almost connecting to the upper anomaly B (Wannamaker et al., 2014). This suggests that the conductor extends parallel to the subduction but that conductors on our profile are spatially intermittent, with anomaly E being clearly delineated from anomaly B.

Temperature modeling (Gao & Wang, 2017) places anomaly E within a thermal window of 400–500 °C, consistent with the dehydration of brucite within serpentinite and a release of up to 11 wt% water (Peacock & Bostock 2025, Evans 2004, Schwartz et al., 2013). The hypothesis that anomaly E reflects fluid release from metamorphic dehydration reactions is supported by the fact that the anomaly is represented by a low P/S wave velocity anomaly (Ramachandran et al., 2006) and lower density (Clowes et al., 1997). However, newer publications contrast these findings (Ojo et al., 2025). Possible other dehydration reactions are based on the P-T phase transformations of the oceanic crust. Hacker et al., (2003) published an analysis of the pressure and temperature-controlled phase relations for northern Cascadia margin. Two major phase transformations of greenschist to amphibolite and eclogites facies may cause fluid release. In this case the released fluid would have ascended from the slab top and been trapped beneath the overriding plate.

However, if anomaly E indeed results from elevated fluid content, porosity estimates can be derived from resistivity using empirical relations. Rock resistivity depends mainly on the poro-space filling's resistivity and its salinity and temperature. Using the model of Sakuma and Ichiki (2016), we compute pore fluid conductivity based on the temperature field from Gao & Wang (2017) and modelled pressure estimates. Figure 2 presents the resulting porosity model. We find a small but distinct and delineated increase in porosity of about 1% above the slab for the given anomalies E and C, whereas the retrieved bulk conductivity can't be explained by lithostatic and thermal parameters.

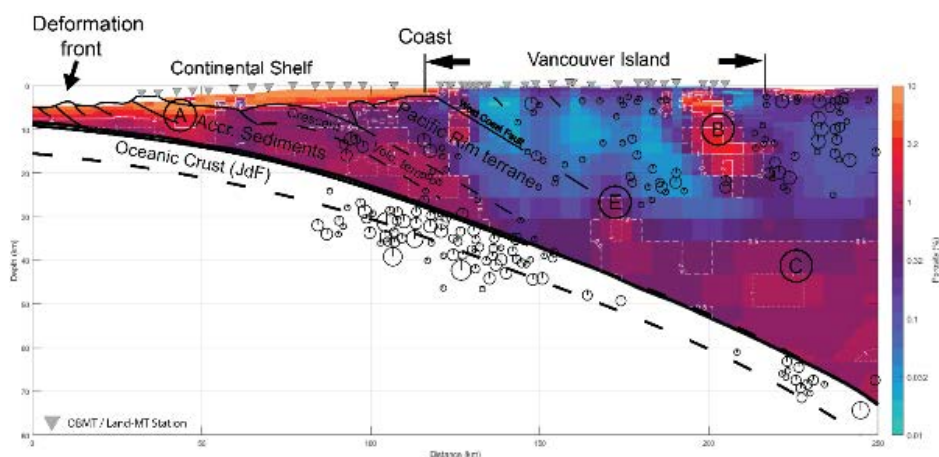


Figure 2: Porosity estimates in percent derived from bulk resistivity model shown in figure 1. For the conversion of bulk resistivity, we assumed Archie's Law ($a = 1$, $m = 1.5$, $S = 1$, $n = 2$) and temperature and pressure dependent fluid conductivity calculations based on a molecular dynamics approach from Sakumo & Ichiki (2016).

Conclusions

Our newly generated 3D resistivity model enhances the previously available datasets by offering a higher resolution especially offshore Vancouver Island. We find distinct anomalies with increased conductivity that give new insights into possible fluid distribution and structural features of the Cascadia subduction zone. The anomalies include dehydration in the subducted sediments in shallow depths offshore Vancouver Island, higher conductivities along major fault lines between accreted terranes and large anomaly beneath eastern Vancouver Island which may represent up-thrusted sediments and mudstones of the Nanaimo Group. The most interesting anomaly at 25–35 km depth beneath Vancouver Island has been imaged before but with sparse, low-resolution data. The presence of the same anomaly on a more southern profile suggests that the conductor is not a local feature but runs parallel to the subduction axes beneath Vancouver Island. The interpretation is difficult, but spatial localization and thermal constraints support the link to fluid release by phase transitions, such as the brucite dehydration within serpentinite or the eclogitization of mafic rocks. Porosity estimates that respect both the thermal and pressure regime hereby suggest an increase of about 1% in the fluid saturated pore-space for the conductors beneath Vancouver Island.

References

- Avdeeva A, Avdeev D & Jegen M, Detecting a salt dome overhang with magnetotellurics: 3D inversion methodology and synthetic model studies, *Geophysics* 2012, 77, E251–E263, doi:10.1190/geo2011-0167.1.
- Clowes RM, Brandon MT, Green AG & Yorath CJ, Sutherland Brown A., Kanasewicheh R., Spencer C., LITHOPROBE--southern Vancouver Island: Cenozoic subduction complex imaged by deep seismic reflections, *Canadian Journal of Earth Sciences* 1987, 24, 31–51.
- Clowes RM, Yorath CJ & Hyndman RD, Reflection mapping across the convergent margin of western Canada, *Geophysical Journal of the Royal Astronomical Society* (1987), 89, 79–84.
- Clowes RM, Baird DJ & Dehler SA, Crustal structure of the northern Cascadia subduction zone, southwestern British Columbia, from potential field and seismic studies, *Can. J. Earth Sci.* 1997, 34, 317–335.
- Evans BW, The serpentinite multisystem revisited: chrysotile is metastable, *International Geology Review* 2004, 46, 479–506, doi:10.2747/0020-6814.46.6.479
- Gao X & Wang K, Rheological separation of the megathrust seismogenic zone and episodic tremor and slip, *Nature* 2017, 543, 416–419, doi:10.1038/nature21389
- Green A, Clowes R & Yorath C, Seismic reflection imaging of the subducting Juan de Fuca plate, *Nature* 1986, 319, 210–213. doi:10.1038/319210a0.
- Hacker BR, Abers GA & Peacock SM, Subduction factory 1. Theoretical mineralogy, densities seismic wave speeds , and H₂O contents, *J. Geophys. Res.* 2003, 108, 2029, doi:10.1029/2001JB001127,B1.
- Hyndman RD, Yorath CJ, Clowes RM & Davis EE, The Northern Cascadia subduction zone at Vancouver Island--Seismic structure and tectonic history, *Can. J. Earth Sci.* 1990, 27,313-329, doi:10.1139/e90-030.
- Moorkamp M, Heincke B, Jegen M, Roberts AW & Hobbs RW, A framework for 3-D joint inversion of MT, gravity and seismic refraction data, *Geophys. J. Int.* 2011, 184, 477–493, doi:10.1111/j.1365-246X.2010.04856.x.
- Peacock SM & Bostock MG, Serpentinization of the forearc mantle wedge in subduction zones: revisiting Roy D. Hyndman's seminal contributions 25 years later, *Can. J. Earth Sci.* 2025, 62, 758–771, doi: 10.1139/cjes-2024-0082.

Preston LA, Creager KC, Crosson RS, Brocher TM & Trehu AM, Intralab earthquakes: dehydration of the Cascadia Slab, *Science* 2003, 302, 1197–1200.

Quist AS & Marshall WL, Electrical conductances of aqueous sodium chloride solutions from 0 to 800° and at pressures to 4000 bars, *J. Phys. Chem.* 1968, 72(2), 684–703.

Ramachandran K, Hyndman RD & Brocher TM, Regional P wave velocity structure of the northern Cascadia subduction zone, *Journal of Geophysical Research* 2006, 111(B12), B12301, doi:10.1029/2006JB004437.

Sakuma H & Ichiki M, Electrical conductivity of NaCl-H₂O fluid in the crust, *J. Geophys. Res. Solid Earth* 2016, 121, 577–594, doi:10.1002/2015JB012219.

Schwartz S, Guillot S, Reynard B, Lafay R, Debret B & Nicollet C, Pressure–temperature estimates of the lizardite/antigorite transition in high pressure serpentinites, *Lithos* 2013, 178, 97–210. doi:10.1016/j.lithos.2012.11.023.

Soyer W & Unsworth MJ, Deep electrical structure of the northern Cascadia (British Columbia, Canada) subduction zone: implications for the distribution of fluids, *Geology* 2006, 34, 53–56, doi:10.1130/G21951.1.

Wannamaker PE, Evans RL, Bedrosian PA, Unsworth MJ, Maris V & McGary RS, Segmentation of plate coupling, fate of subduction fluids and modes of arc magmatism in Cascadia, inferred from magnetotelluric resistivity, *Geochem. Geophys. Geosyst.* 2014, 15, 4230–4253, doi:10.1002/2014GC005509.

Yorath CJ, Green AG, Clowes RM, Sutherland Brown A, Brandon MT, Kanasewiceh R, Hyndman RD & Spencer C, LITHOPROBE, southern Vancouver Island: seismic reflection sees through Wrangellia to the Juan de Fuca plate, *Geology* 1985, 13, 759–762.

SO294

Investigating the occurrence and kinematic role of proto-thrusts along the northern Cascadia Margin

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

W. Schäfer, M. Riedel, G. Crutchley, H. Kopp

Background

Large subduction earthquakes and their associated tsunamis are among the greatest natural hazards for densely populated coastal regions worldwide. This study focuses on the northern Cascadia continental margin off the west coast of Canada, where the oceanic Juan de Fuca plate subducts beneath the continental North American plate with a convergence rate of about 45mm per year (e. g. DeMets et al., 2010). Historically, this region has experienced several megathrust earthquakes with magnitudes greater than MW 8.5, with the last major earthquake occurring in 1700 A.D., as confirmed by tsunami records in Japan, over 7000 km away from the hypocenter on the other side of the Pacific (Satake et al., 2003). Today, the Cascadia margin represents one of the areas in the world, which is considered most prone to a major subduction earthquake in the foreseeable future.

Proto-thrusts mark the onset of deformation at the toe of subduction accretionary wedges and are typically represented in reflection seismic sections as closely spaced, small-displacement, often intersecting reverse faults seaward of the primary frontal thrust. The existence of proto-thrusts has been documented at multiple subduction zones around the world (e. g. Moore et al., 1990; Davey et al., 1986), yet only a few studies describe their kinematic role in frontal accretion at the subduction front.

SO294 Seismic Experiment (CLOCKS project)

During RV SONNE cruise SO294, an extensive dataset consisting of high-resolution bathymetry and multichannel seismic data as well as coincident echosounder profiles was acquired along the northern Cascadia margin. The 14 multichannel seismic lines utilized in this study (Figure 1) were recorded using a streamer with about 290m active length and 1.56m group spacing in combination with a single 355 in³ GI gun fired in harmonic mode in a 10s interval, resulting in a shotpoint distance of about 25m. The processing workflow included frequency filtering, 2D spike removal, spherical divergence gaining (t^2), velocity analysis, NMO correction, stacking and finite difference time-migration. The survey was designed that all 14 profiles cross the deformation front perpendicularly to be able to compare angles etc. between profiles.

As a valuable addition, the high-resolution bathymetric data collected using a hull-mounted EM122 and EM170 system was utilized to analyze the surrounding morphology and larger-scale tectonic structures, such as strike-slip faults or ridges. For additional velocity information, we considered three legacy seismic profiles that were acquired in 1989 with a longer streamer than the recent data. These profiles are lower in resolution, but provide more precise velocity information than the CLOCKS profiles.

Characteristics of the deformation front

The acquired data allows the first systematic characterization and investigation of the deformation front and the occurrence of proto-thrusts along the deformation front offshore Vancouver Island (Figure 1). Within this study, we mainly aim to understand the distribution and kinematic role of proto-thrusts regarding strain accommodation in this area. The deformation front is well marked by a series of ridges in the high-resolution bathymetry and appears fragmented into small-scale segments, varying between 4km and 10km in length. The first main thrust of the accretionary prism is traceable throughout the seismic profiles and mostly follows the frontal ridges seen in the bathymetry. We observe mainly seaward verging frontal thrusts, whereas a significantly long segment of the margin features landward verging frontal thrusts.

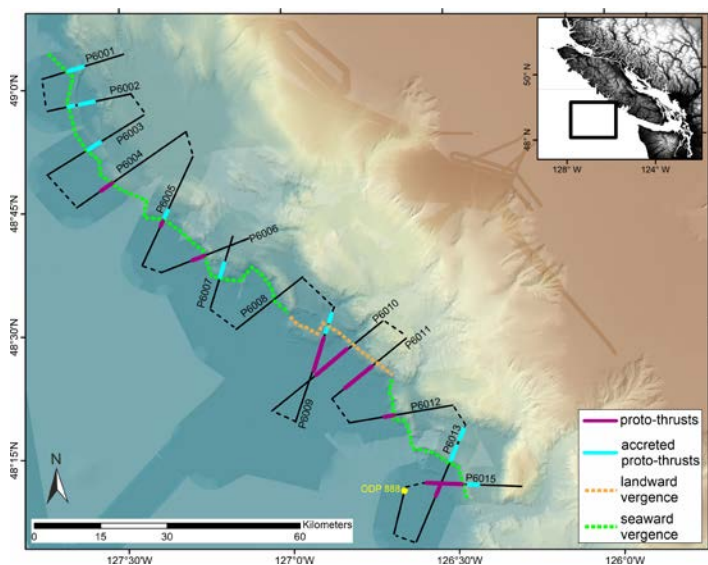


Figure 1: Bathymetric map of the study area with marked deformation front characteristics and detected proto-thrust zones.

The data reveal a clear correlation between the occurrence and characteristics of proto-thrusts and the vergence of the main frontal thrust of the accretionary prism. In the case of a landward verging main frontal thrust, the proto-thrust zone is widest and the proto-thrusts are of mixed vergence (e. g. Figure 2). In contrast, if the main frontal thrust is seaward verging, the proto-thrusts are sparse and predominantly seaward verging. Overall, the proto-thrusts are bounded to a specific sediment layer and do not penetrate further up- or downwards.

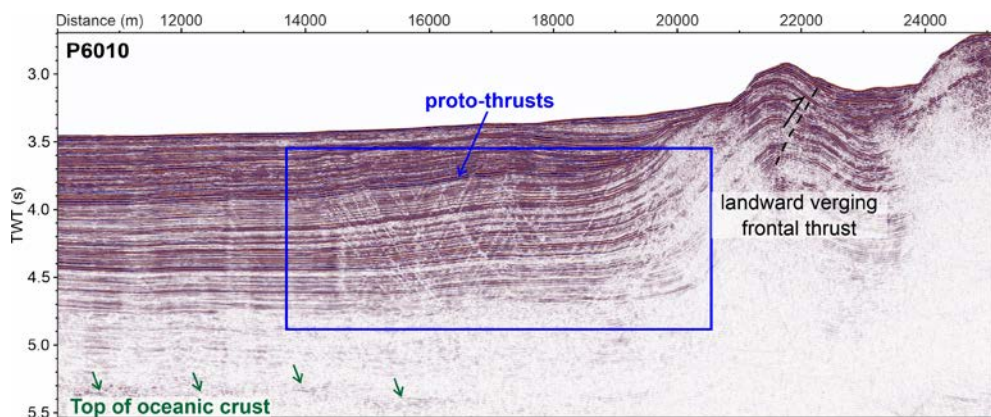


Figure 2: Exemplary multichannel seismic profile P6010 (for location see Figure 1) from SO294 crossing the deformation front perpendicularly, featuring a landward verging frontal thrust accompanied by a ~6km long proto-thrust zone.

Velocity analyses along legacy multichannel seismic data reveal signs of significant compaction from lateral compression seaward of the deformation front in regions associated with proto-thrust development. For different analyzed profiles, the length of the velocity anomaly reflects the length of the respective proto-thrust zone. No significant velocity anomaly is observed where there are no proto-thrusts observed in the seismic line. The compaction-related velocity increase in the proto-thrust zones indicates that the proto-thrusts may accommodate up to 20% of the strain accumulation. We also observe similar networks of proto-thrusts landward of the main frontal thrust. Their contribution to total shortening within the prism remains unknown, as well as the question of whether they are still active. The effective combined shortening by proto-thrusts and lateral pore space compaction can be used in refining the regional geo-hazard model that currently overlooks these processes.

References

- Davey FJ, Hampton M, Childs J, Fisher MA, et al., Structure of a growing accretionary prism, Hikurangi margin, New Zealand, *Geology* 1986, 14(8), 663–666.
- DeMets C, Gordon RG & Argus DF, Geologically current plate motions, *Geophysical Journal International* 2010, 181(1), 1–80, doi: <https://doi.org/10.1111/j.1365-246X.2009.04491.x>.
- Moore GF, Shipley TH, Stoffa PL, Karig DE, et al., Structure of the Nankai Trough accretionary zone from multichannel seismic reflection data, *Journal of Geophysical Research* 1990, 95, 8753–8765, doi: 10.1029/JB095iB06p08753.
- Satake K, Wang K & Atwater BF, Fault slip and seismic moment of the 1700 Cascadia earthquake inferred from Japanese tsunami descriptions, *Journal of Geophysical Research* 2003, 108(B11), 2535, doi: 10.1029/2003JB002521.

SO294

CASCADIA CO₂

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

M. Soleimani Monfared, J. Bialas, M. Riedel, C. Papenberg

Ocean Networks | Canada

M. Scherwath

SO294 – CASCADIA CO₂

The SO294 CASCADIA CO₂ project was carried out as a secondary use of the SO294 CLOCKS cruise. Aim of the project was to utilize four component ocean-bottom seismometers investigating basalt complexes for their capabilities to serve as a storage site for CO₂ injection.

As the IPCC reports, predicted climate change scenarios, and a multitude of scientific studies show, it is already necessary to remove gigatons of CO₂ from the atmosphere and store it permanently in order to limit global warming despite the transition to a CO₂-neutral society (IPCC, 2023). Current geological CO₂ storage projects typically use porous reservoirs in sedimentary basins, such as depleted oil fields or saline aquifers (Geological Survey of Denmark and Greenland, 2009). However, permanent trapping takes hundreds to thousands of years (Ajayi et al., 2019) while legacy boreholes require careful risk assessments (Pullen et al., 2025).

CarbFix in Iceland has shown that sequestration in porous basalts has advantages over more traditional approaches, including high hydraulic permeability and rapid mineralization of CO₂, resulting in permanent storage (IEA GHG, 2017). Recent publications on two successful field studies by the CarbFix project report that 95% (CarbFix I) and >60% (CarbFix II) of the injected CO₂ is mineralized within two years (Clark et al., 2020; Gunnarsson et al., 2015). The permanent sequestration of CO₂ in porous basalt rock means that, once mineralized, the CO₂ cannot escape or cause groundwater contamination or blowouts, making it a publicly acceptable model for carbon storage.

The CarbonSAFE Cascadia project investigated the potential of a site for CO₂ storage in the Cascadia Basin on the eastern flank of the Juan de Fuca Ridge. The Canadian initiative Solid Carbon intends to continue this research and develop a test injection with supercritical CO₂. The available IODP boreholes are aligned in a NNE direction along the strike of the ridge segments but would not allow monitoring of the lateral extent of the injected gas plume. In order to avoid costly observation wells for a fundamental investigation of the physical parameters before and during the injection phase, geophysical remote sensing of subsurface parameters should provide an adequate database for modeling and monitoring. The CASCADIA CO2 project aims to investigate these possibilities, with OBS being used to develop depth models of the subsurface structure and distribution of compressional and converted shear wave velocities.

22 OBS were deployed on the intersecting profiles P1000 and P1002 (Figure 1). 21 instruments provided excellent data for further modeling. Since the shear wave velocity (Vs) in rock is significantly lower than the compression wave velocity (Vp), the smaller reflection angles illuminate a narrower area beneath the device than is the case with Vp. To ensure reliable interpretation the OBS were deployed in groups of closer intervals in order to achieve a greater profile distance. An airgun array (2840 cinch) consisting of three G-gun clusters served as the seismic source and was fired every 60 seconds.

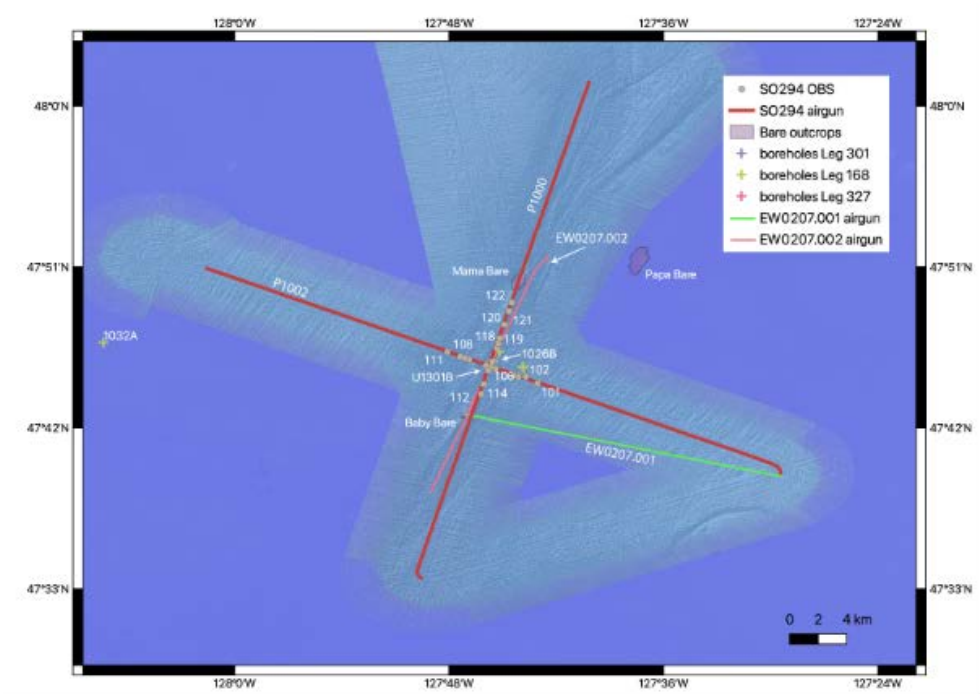


Figure 1: Map of the working area.

Based on reflection seismic lines, an initial structural model was created, and steep-angle reflections in the OBS data were assigned to the horizons of the reflection lines. Using the PASTEUP code (Fujie et al., 2008), the travel times of the reflections and refracted waves from the sediment, basement, and Moho were identified and picked. Using forward modeling of all 21 OBS data sets, a Vp velocity model was first created (code MODELING by Fujie et al., 2008). The Vp model was used as the initial model for tomographic inversion according to Korenaga et al. (2000). Variants of the initial models and grid resolutions were investigated in the tomography model, and a grid with a horizontal grid width of 125 m and a vertical grid width of 75 m was selected as a reference for further processing. For both models of profiles P1000 and P1002, the structures of the sediment cover depicted in the multichannel seismic data could be modeled in the velocity profile. In addition to the multichannel seismic data, variations in the velocity-depth distribution indicate slight structuring within the basement. Increased velocities below the Mama Bare structures and the Baby Bare structure suggest that the roots of the structures extend to a depth of 3.5 km. Model P1002 shows a decrease in velocities towards the east below the basement. Reflections from the Moho are modeled with a depth of 10 km, and show a horizontal layering on both profiles.

Based on these Vp models, the converted shear waves were modeled next. The reflection point of the seismic ray path was used as the reference point for the conversion (see also Zhu et al., 2020). The grid sizes of the velocity models were retained. Both Vs models show no distinct structures below the basement. In the Vs model of profile P1000, no significant velocity variations within the sediments can be observed along the profile. At the top of the basement, the Mama Bare and Baby Bare structures stand out due to slightly increased Vs velocities. South of the Mama Bare structure, there is a noticeable local reduction in velocity, which decreases to a depth of about 8 km, coincident with an event in the reflection seismic data. In the Vs model of the intersecting profile P1002, limited areas with reduced velocities can be observed. These velocity anomalies coincide with small depressions in the topography of the basement top. However, they are not formed in the Vp model.

To improve the analysis of possible variations in physical parameters in the subsurface, the Vp/Vs models were built for both profiles. With regard to the basalt properties, the high Vp/Vs values of the sediments were excluded. The Vp/Vs ratio is consistently below 2 and thus matches values determined for various areas in the nearby Endeavour segment by Kim et al. (2019) for the upper crust.

In profile P1000, the basement is characterized by a balanced Vp/Vs ratio down to a depth of approximately 6 km, from which the Mama Bare and Baby Bare structures do not stand out. South of Mama Bare, the observed reduced Vs values are reflected by a locally elevated Vp/Vs ratio (1.82). This anomaly, approximately

2 km wide, dips to a depth of 8 km. The intersecting profile P1002 is characterized by a relatively high Vp/Vs ratio down to a depth of 4 km. This is caused by the comparatively low Vs velocities. Other areas of locally increased Vp/Vs ratio increase up to a ratio of 1.9. From a depth of 4 km, the Vp/Vs ratio is relatively balanced up to a depth of 7 km, with average values of around 1.75 (P1002), which is slightly lower than the average of 1.8 in profile P1000.

For further investigation of potential signatures of deeper structures in the OBS data, mirror imaging was applied to the wavefield of the first water multiples (Grion et al., 2007). The hydrophone data from 19 OBS stations along lines P1000 and P1002 were migrated individually and then stacked to map lines P1000 and P1002 accordingly. The OBS data could not reveal any additional coherent phases within the basalt layer. In order to better image the complex and rugged geometry of the basalt layers without aliasing, a denser shot spacing and a denser receiver spacing would be necessary.

The east-west (125°) oriented profile P1002 runs perpendicular to the spreading axis of the Juan de Fuca Ridge (JDF) and depicts the upper edge of the basement with a correspondingly rough topography, which is also reported in other studies (Kim et al., 2019; Nedimović et al., 2009). The north-south (35°) oriented profile P1000 with the Baby Bare and Mama Bare structures runs parallel to the JDF on an elevation referred to as the “Secondary Ridge” (Hutnak et al., 2006; Zühlsdorff et al., 2005). Seismic and heat flow studies in the vicinity of profiles P1000 and P1002 have been evaluated by Hutnak et al. (2006) and Zühlsdorff et al. (2005), among others, but focus primarily on sedimentary structures. Hutnak et al. (2006) describe the region of the study area with conductive heat transport. Wheat et al. (2004) surveyed the region around the Bare Outcrop Group with the submersible Alvin and describe, in addition to largely conductive heat transport, the flow of ground water through the basement from Grizzly Bare to Baby Bare and Mama Bare. The anomalies in the Vp/Vs ratio presented here suggest that at least Mama Bare may contribute to further heat flow via deeper roots.

References

- Ajayi T, Gomes JS & Bera A, A review of CO₂ storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches, *Petroleum Science* 2019, v. 16, no. 5, p. 10285–1063.
- Clark DE, Oelkers EH, Gunnarsson I, Sigfússon B, Snæbjörnsdóttir SÓ, Aradóttir ES & Gíslason SR, CarbFix2: CO₂ and H₂S mineralisation during 3.5 years of continuous injection into basaltic rocks at more than 250 °C, *Geochimica et Cosmochimica Acta* 2020, v. 279, p. 45–66.

Fujie G, Kasahara J, Murase K, Mochizuki K & Kaneda Y, Interactive analysis tools for the wide-angle seismic data for crustal structure study (Technical Report), Exploration Geophysics 2008, v. 39, no. 1, p. 26.

Geological Survey of Denmark and Greenland, EU GeoCapacity - Assessing European Capacity for Geological Storage of Carbon Dioxide, Geological Survey of Denmark and Greenland 2009, SES6-518318.

Grion S, Exley RJK, Manin M, Miao X-G, Pica A, Wang Y, Granger P-Y & Ronen S, Mirror imaging of OBS data, First Break 2007, v. 25, p. 1-6.

Gunnarsson G, Kristl  nsson BR, Gunnarsson I & J  l  sson BM, Reinjection into a Fractured Reservoir – Induced Seismicity and Other Challenges in Operating Reinjection Wells in the Hellishei i Field, SW-Iceland, *in* Proceedings World Geothermal Congress 2015, Melbourne, Australia, 2015: Melbourne, Australia, p. 9.

Hutnak M, Fisher AT, Z  hlsdorff L, Spiess V, Stauffer PH & Gable CW, Hydrothermal recharge and discharge guided by basement outcrops on 0.7–3.6 Ma seafloor east of the Juan de Fuca Ridge, Observations and numerical models: Geochemistry, Geophysics, Geosystems 2006, v. 7, no. 7, p. n/a-n/a.

IEA GHG, CCS deployment in the context of regional developments in meeting long-term climate change objectives, IEA GHG 2017.

IPCC, Summary for Policymakers, *in* Team, C. W., Lee, H., and Romero, J., eds., Climate Change 2023, Synthesis Report, A Report of the Intergovernmental Panel on Climate Change, Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change: Geneva, Switzerland, IPCC 2023, p. 36.

Kim E, Toomey DR, Hooft EEE, Wilcock WSD, Weekly RT, Lee SM & Kim YH, Upper Crustal Vp/Vs Ratios at the Endeavour Segment, Juan de Fuca Ridge, From Joint Inversion of P and S Traveltimes: Implications for Hydrothermal Circulation, Geochemistry, Geophysics, Geosystems 2019, v. 20, no. 1, p. 208–229.

Korenaga J, Holbrook WS, Kent GM, Kelemen PB, Detrick RS, Larsen HC, Hopper JR & Dahl-Jensen T, Crustal structure of the southeast Greenland margin from joint refraction and reflection seismic tomography, J. Geophys. Res. 2000, v. 105, no. B9, p. 21591.

Nedimovi  MR, Bohnenstiehl DR, Carbotte SM, Pablo Canales J & Dziak RP, Faulting and hydration of the Juan de Fuca plate system, Earth and Planetary Science Letters 2009, v. 284, no. 1–2, p. 94–102.

Pullen B, Cahill A & Arnold D, Differentiating legacy wellbores in the scottish north sea using multi-criteria decision analysis with a view to minimising containment risk for carbon capture and storage, *International Journal of Greenhouse Gas Control* 2025, v. 142.

Wheat CG, Mottl MJ, Fisher AT, Kadko D, Davis EE & Baker E, Heat flow through a basaltic outcrop on a sedimented young ridge flank, *Geochemistry, Geophysics, Geosystems* 2004, v. 5, no. 12.

Zhu J, Canales JP, Han S, Carbotte SM, Arnulf A & Nedimović MR, Vp/Vs Ratio of Incoming Sediments Off Cascadia Subduction Zone From Analysis of Controlled-Source Multicomponent OBS Records, *Journal of Geophysical Research, Solid Earth* 2020, v. 125, no. 6.

Zühlsdorff L, Hutnak M, Fisher AT, Spiess V, Davis EE, Nedimovic M, Carbotte S, Villinger H & Becker K, Site surveys related to IODP Expedition 301, ImageFlux (SO149) and RetroFlux (TN116) expeditions and earlier studies, *Proceedings of the IODP* 2005, 301.

SO297

Investigating the seismic structure, geometry and seismicity offshore Northern Chile (25°–27.5°S)

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

A. Warwel, D. Lange, A. Dannowski, I. Klaucke, H. Kopp

Universidad de Chile | Santiago de Chile, Chile

E. Contreras-Reyes

Pontificia Universidad Católica de Chile | Santiago de Chile, Chile

M. Moreno

Pontificia Universidad Católica de Valparaíso | Valparaíso, Chile

J. Díaz-Naveas

The Northern Chilean Margin

The Chilean margin is shaped by the subduction of the oceanic Nazca Plate beneath the continental South American Plate, forming a highly active plate boundary repeatedly known to generate tsunamigenic megathrust earthquakes (e. g. Ruiz & Madariaga, 2018; Comte & Pardo, 1991; Kukowski & Oncken, 2006). Although subduction occurs along the entire Chilean margin, the Atacama region (24°S–27.5°S) in northern Chile has remained unaffected by large earthquakes (> MW 8) for more than a hundred years. In this region, the inter-seismic phase is characterized by elevated seismic activity, including earthquakes up to MW 7, and a high degree of locking, in particular in the offshore domain (e. g. Klein et al., 2018, 2023; González-Vidal et al., 2023). However, while the geology, structure and seismicity of the continental margin have been intensively studied within the last decades (e. g. Yáñez-Cuadra et al., 2022; González-Vidal et al., 2023; Leon-Rios et al., 2024; Münchmeyer et al., 2025), the offshore domain, including the subduction trench, the incoming Nazca Plate and the Copiapó and Taltal Ridges, is significantly less explored.

SO297 Seismic Refraction Experiment

In the course of SO297, two amphibious 2D wide-angle seismic refraction profiles were acquired along the Copiapó (~27.5°S) and Taltal (~25°S) Ridges, respectively (Lange et al., 2023). Active seismic data were recorded on 36 (Copiapó) and 40 (Taltal) Ocean-Bottom-Seismometers/Ocean-Bottom-Hydrophones, which were spaced between 3 km and 7 km apart and covered the incoming Nazca Plate, several seamounts of the Copiapó and Taltal Ridges, the deep-sea subduction trench as well as the marine forearc. In addition, the profiles were extended onshore by 10 (Copiapó) and 13 (Taltal) land seismometers, which also recorded the offshore-generated seismic signals. The data were inverted for the P-wave (Copiapó) and P- and S-wave (Taltal) velocity structure and, combined with new high-resolution bathymetry, allow the characterization of detailed structure of the incoming plate and of the Copiapó and Taltal Ridges as well as the geometry of the down-going slab. In addition, the obtained velocities were used to accurately locate earthquakes recorded on the temporary, land-based seismometers. The resulting seismicity catalog enables us to analyze the seismicity structure and link it to the characteristics of the incoming plate.

Copiapó area (~27.5 °S)

The 2D seismic refraction profile offshore Copiapó exhibits a typical oceanic crust thickness of 6–7 km and seismic P-wave velocities between 3.0 and 7.3 km/s with slightly lower velocities and increased thickness underneath the Copiapó Ridge seamounts (Figure 1). The latter is most likely due to predominantly extrusive formation. Elevated velocities underneath one of the seamounts indicate a local region of magmatic underplating, while bending-related faults visible in the bathymetry and reduced mantle velocities near the trench indicate mantle hydration. The subduction angle of the down-going Nazca plate smoothly increases from 12° below the marine forearc to 22° at greater depths (40–60 km), with no abrupt change in the dip angle as observed at ~22°S (Figure 1) (cf. Contreras-Reyes et al., 2012). The local seismicity off- and onshore Copiapó shows three separated bands of earthquakes sub-parallel to the down-going plate that are most likely related to the plate interface, the oceanic Moho and the Double Benioff Zone. The largest event (MW 5.9) during our observation period (December 2022–June 2023) and its aftershocks occurred in the deepest band ~20 km below the subduction interface. Along the interface, seismicity is most pronounced in areas of high locking offshore, whereas areas of low coupling are characterized by previously observed slow slip events and sparse seismicity.

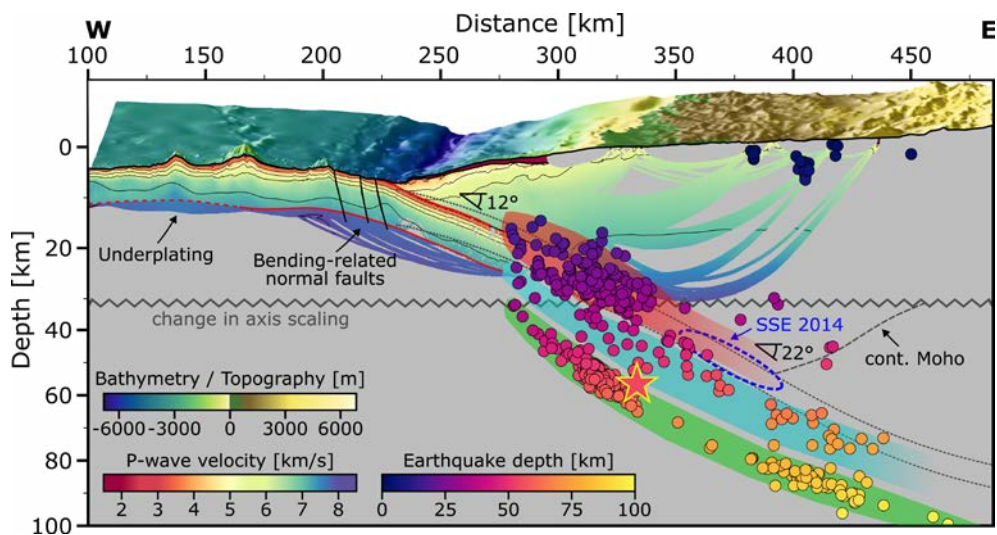


Figure 1: P-wave velocity model, slab geometry and local seismicity at the Copiapó Ridge at ~27.5°S.

Taltal area (~25°S)

The geometry and velocity structure of the incoming plate and the structure of the Taltal Ridge seamounts exhibit similar characteristics to the incoming plate and Copiapó Ridge seamounts at 27.5°S. The high-resolution bathymetry reveals extensional E-W oriented horst-and-graben structures that are different from other horst-and-graben structures previously observed along the Chilean margin. We attribute them to a north-south-directed extension within the last 10 million years and suggest that, together with N-S oriented bending-related normal faults, they create permeable pathways that allow seawater to infiltrate the oceanic crust and upper mantle (Figure 2). This process leads to hydration and serpentinization, resulting in the observed reduced P- and S-wave velocities ($V_p \approx 7.5$ km/s; $V_s \approx 3.8$ km/s) and elevated V_p/V_s ratios exceeding 1.9. In segments of the upper mantle near the trench, serpentinization is estimated to reach up to 30%. In contrast to the observed faults, the seamounts of the Taltal Ridge seem not to be the main driver of the hydration, as they are not yet affected by the plate bending, and thus, their inherited weakness zones have not been reactivated. During subduction, the water is released causing dehydration-related earthquakes explaining the increase in observed seismicity between 70 km and 100 km depth at ~25°S (Figure 2).

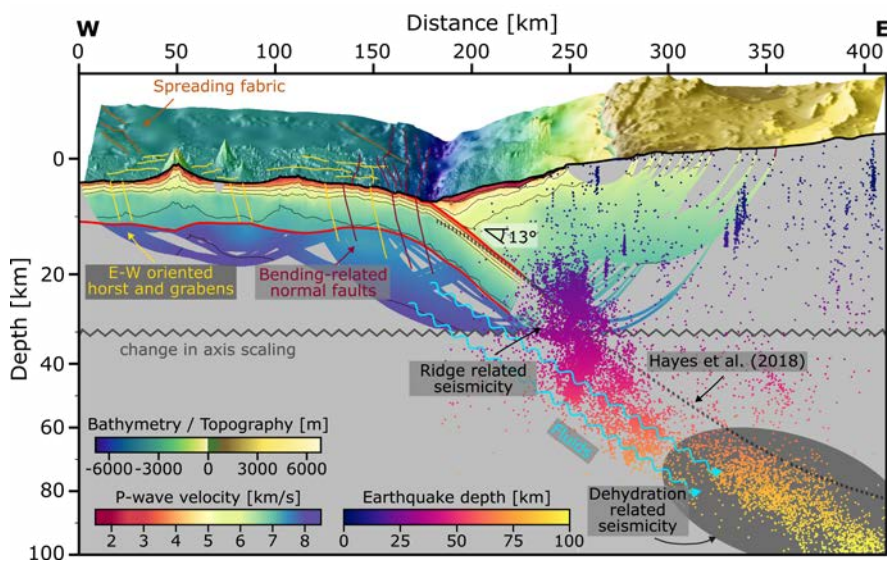


Figure 2: Schematic representation of the incoming and overriding plate, faults and the seismicity at the Chilean subduction zone at the Taltal Ridge at ~25.5°S.

References

- Comte D & Pardo M, Reappraisal of great historical earthquakes in the northern Chile and southern Peru seismic gaps, *Natural Hazards* 1991, 4, 23–44, doi: <https://doi.org/10.1007/BF00126557>.
- Contreras-Reyes E, Jara J, Grevemeyer I, Ruiz S, et al., Abrupt change in the dip of the subducting plate beneath north Chile, *Nature Geoscience* 2012, 5(5), 342–345, doi: <https://doi.org/10.1038/ngeo1447>.
- González-Vidal D, Moreno M, Sippl C, Baez JC, et al., Relation between oceanic plate structure, patterns of interplate locking and microseismicity in the 1922 Atacama seismic gap, *Geophysical Research Letters* 2023, 50(15), e2023GL103565, doi: <https://doi.org/10.1029/2023GL103565>.
- Klein E, Duputel Z, Zigone D, Vigny C, et al., Deep transient slow slip detected by survey GPS in the region of Atacama, Chile, *Geophysical Research Letters* 2018, 45(22), doi: <https://doi.org/10.1029/2018GL080613>.
- Klein E, Vigny C, Duputel Z, Zigone D, et al., Return of the Atacama deep slow slip event: The 5-year recurrence confirmed by continuous GPS, *Physics of the Earth and Planetary Interiors* 2023, 334, 106970, doi: <https://doi.org/10.1016/j.pepi.2022.106970>.

Kukowski N & Oncken O, Subduction Erosion – The “Normal” Mode of Fore-Arc Material Transfer along the Chilean Margin?, in: Oncken O, Chong G, Franz G, Giese P, Götze HJ, Ramos VA, Strecker MR, Wigger P (eds.), *The Andes: Active Subduction Orogeny*, Springer 2006, 217–236, doi: https://doi.org/10.1007/978-3-540-48684-8_10.

Lange D, Kopp H, Dannowski A, Klaucke I, et al., A high-resolution controlled-source seismic experiment offshore Taltal to elucidate structural controls on megathrust slip, Cruise No. SO297, February 23–April 11, 2023, Talcahuano (Chile)–Guayaquil (Ecuador), 2023, doi: https://doi.org/10.48433/cr_so297.

Leon-Rios S, Reyes-Wagner V, Calle-Gardella D, Rietbrock A, et al., Structural characterization of the Taltal segment in northern Chile between 22°S and 26°S using local earthquake tomography, *Geochemistry Geophysics Geosystems* 2024, 25(5), e2023GC011197, doi: <https://doi.org/10.1029/2023GC011197>.

Münchmeyer J, Molina-Ormazabal D, Marsan D, Langlais M, et al., Characterizing the Atacama segment of the Chile subduction margin (24°S–31°S) with >165,000 earthquakes, *Journal of Geophysical Research: Solid Earth* 2025, 130(7), e2025JB031256, doi: <https://doi.org/10.1029/2025JB031256>.

Ruiz S & Madariaga R, Historical and recent large megathrust earthquakes in Chile, *Tectonophysics* 2018, 733, 37–56, doi: <https://doi.org/10.1016/j.tecto.2018.01.015>.

Yáñez-Cuadra V, Ortega-Culaciati F, Moreno M, Tassara A, et al., Interplate coupling and seismic potential in the Atacama seismic gap (Chile): Dismissing a rigid Andean sliver, *Geophysical Research Letters* 2022, 49(11), e2022GL098257, doi: <https://doi.org/10.1029/2022GL098257>.

SO299/2

Underway bio-optical characterization of surface waters in the Indian Ocean – from Singapore to Mauritius

Authors

Institute for Chemistry and Biology of the Marine Environment | Wilhelmshaven, Germany

J. Wollschläger, D. Voß, R. Henkel, J. Oelker

Abstract

Hyperspectral bio-optical measuring methods are essential elements of modern ocean observation and support both basic and applied research (e. g. satellite observations or bio-optical modeling) with high-resolution data sets. The light field and the derived ocean color is an essential climate variable (ECV) and relevant for a better understanding of dynamics and processes of biogeochemical and physical variables with optical signatures (GCOS, 2011; Garaba & Zielinski, 2013; GCOS, 2021). Natural light is a basic requirement for life on earth, providing energy to warm the land and sea, driving global atmospheric and ocean currents, enabling photosynthesis, and affecting the health and behavior of many organisms (Kirk, 2011). Natural water bodies and their components are thus strongly influenced by light abundance. The aquatic primary producers and their community composition is actively influenced by light as a limiting factor (Marinov et al., 2010; Hopwood et al., 2018). Going further, also the carbon export flux is determined by the structure and functioning of the food web and is regulated by the overall level of primary productivity in the euphotic “light flooded” zone (Brix et al., 2006). In turn, the attenuation of light within the water column is dependent on the optically active substances, which are mainly phytoplankton, chromophoric dissolved organic matter (CDOM), and non-algal particles (NAP, e. g. detritus, suspended sediments). Thus, there is a certain degree of feedback between underwater light availability and phytoplankton abundance. But light is not only shaping aquatic ecosystems, it is also a medium of information transport. As the aforementioned water constituents are optically active by absorbing, scattering or emitting light (fluorescence), optical sensors offer the possibility to rapidly collect a variety

of relevant oceanographic parameters (Moore et al., 2009). Thus, they are very suitable to be used as continuously measuring “underway” sensors that provide temporally and spatially highly resolved data sets that contribute to ecosystem assessment. In particular, hyperspectral measurements of the inherent, apparent, or fluorescent optical properties of water can provide data that can be used to acquire or refine new or existing knowledge about important marine processes, e. g. such as primary production or carbon cycling (Kirk, 2011; Wollschläger et al., 2020; Wollschläger et al., 2021; Jemai et al., 2021). In combination with measurements of bulk concentrations of optically active substances, bio-optical data can be used to create or refine regional parameterizations (Wollschläger et al., 2020).

The RV SONNE transit cruise SO299/2 from Singapore to Mauritius (August 15th–September 2nd, 2023) was used to collect a high-resolution set of optical data for surface water characterization combining several ship-based underway measurements with discrete laboratory-based measurements. The Indian Ocean is the third largest ocean in the world, surrounded by Africa, Asia, Australia, and Antarctica. It is influenced by the El Niño-Southern Oscillation (ENSO) and shows the phenomenon of the Indian Ocean Dipole (IOD), affecting the strength of the monsoons in adjacent areas. In the Indian Ocean, also one of the subtropical gyres is located. In general, optical properties of the open ocean have been intensively studied, especially with a focus on remote sensing, and robust algorithms for large-scale prediction of water constituent concentrations have been implemented. Nevertheless, further investigations of the light regime and the bio-optical signatures of the water column are necessary to complete the overall big picture as data for validation of these algorithms are still scarce in many areas of the oceans. Further, new and hyperspectral datasets are required to support upcoming hyperspectral satellite missions like PACE; (Plankton, Aerosol, Cloud, ocean Ecosystem) or CHIME (Copernicus Hyperspectral Imaging Mission for the Environment).

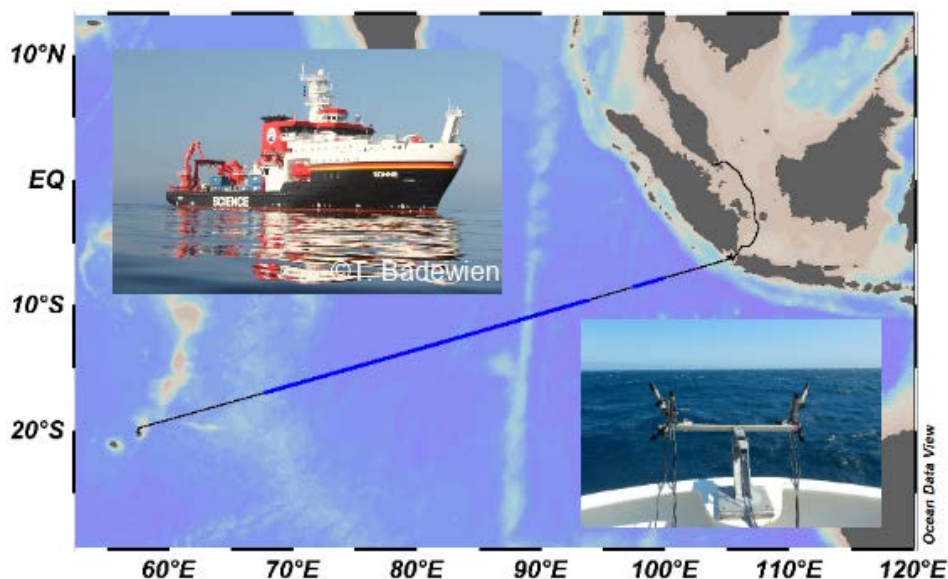


Figure 1: Transit cruise SO299/2 of RV SONNE from Singapore to Mauritius. Underway measurements focussed on international waters. Hyperspectral radiometric setup was installed at the bow of the ship (lower right corner).

In order to characterize important apparent optical properties (e. g., the diffuse attenuation coefficient, remote sensing reflectance, ocean color), a hyperspectral radiometric set-up in front of the ship was installed (TriOS Ramses, Figure 1, lower right corner). In addition, a Pocket-FerryBox System (4H Jena, Germany) measured continuously biogeochemical parameters in the surface water (e. g., salinity, temperature, oxygen, turbidity, and chl-a). Further, discrete samples were taken in defined intervals and analysed on board using benchtop instrumentation, amongst others a point-source integrating cavity absorption meter (PSICAM), to provide absorption and fluorescence characteristics. The collected data are further combined with the FAIR processed data of the German “Underway Research Data” project of the German Marine Research Alliance (DAM). The bio-optical characterization of the transect is used to match with satellite remote sensing in this area (GlobColour) for validation purposes, increasing data availability and can contribute to an understanding of the dynamics and processes in the Indian Ocean on a wider spatial scale.

The development of various phytoplankton related optical data over the course of the transect is shown in Figure 2. There, continuous Pocket-FerryBox (PFB) measurement of chl-a fluorescence are combined with similar data from the ship’s onboard self-cleaning measurement box (SMB) and chl-a estimated from radiometry. For the latter, measured remote sensing reflectance was converted into chl-a using the OC3 algorithm. Despite being from different instruments and

using different optical proxies, the chl-a estimations were in good agreement. This is also true for the different discrete data. During the transect, chl-a increased steadily and showed in the fluorescence data since the 27.08. a diurnal pattern, most likely induced by non-photochemical quenching.

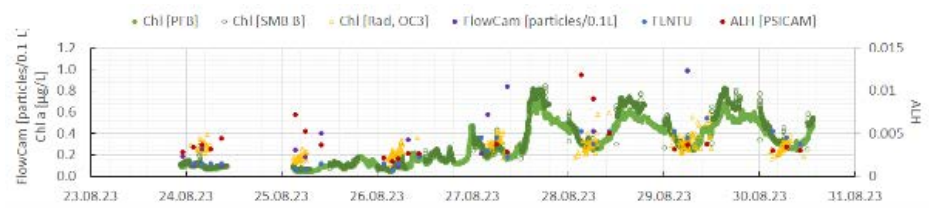


Figure 2: Combined time series of phytoplankton-related data from the transect. Underway data comprise chl-a estimations via fluorometry (Portable FerryBox, PFB; ship self-cleaning measurement box B, SMB B) and radiometry (Rad, converted to chl-a via OC3 algorithm). In comparison discrete data: Cell counts from FlowCam, chl-a fluorescence measurements (FLNTU) and absorption line height (ALH), derived from PSICAM.

References

- Brix H, Gruber N, Karl D M & Bates NR, On the relationships between primary, net community, and export production in subtropical gyres', *Deep-Sea Research Part II: Topical Studies in Oceanography* 2006, 53(5-7), pp. 698-717, doi: 10.1016/j.dsr2.2006.01.024.
- Garaba SP & Zielinski O, Comparison of remote sensing reflectance from above-water and in-water measurements west of Greenland, Labrador Sea, Denmark Strait, and west of Iceland. *Optics Express* 2013, Vol. 21, Issue 13, pp.15938-15950.
- GCOS, The Global Climate Observing System - Systematic Observation Requirements for Satellite-based Data Products for Climate: 2011 Update GCOS-154 (pp. 138) 2021 Update, World Meteorological Organization - Geneva, Switzerland.
- Jemai A, Wollschläger J, Voß D & Zielinski O, Radiometry on Argo Floats: From the Multispectral State-of-the-Art on the Step to Hyperspectral Technology, *Front. Mar. Sci.* 2021, doi: 10.3389/fmars.2021.676537/full.
- Kirk JT, *Light and photosynthesis in aquatic ecosystems*, Cambridge university press, 2011.

Hopwood MJ, Carroll D, Browning TJ, Meire L, Mortensen J, Krisch S & Achterberg EP, Non-linear response of summertime marine productivity to increased meltwater discharge around Greenland, *Nature Communications* 2018, 9, 3256, doi: 10.1038/s41467-018-0548.

Marinov I, Doney SC & Lima ID, Response of ocean phytoplankton community structure to climate change over the 21st century: partitioning the effects of nutrients, temperature and light, *Biogeosciences* 2010, 7(12), p.3941.

Moore C, Barnand A, Fietzek P, Lewis M, Sosik H, White S & Zielinski O, Optical tools for ocean monitoring and research, *Ocean Science* 2009, 5, pp 661–684, doi:10.5194/os-5-661-2009.

Wollschläger J, Tietjen B, Voß D & Zielinski O, An Empirically Derived Trimodal Parameterization of Underwater Light in Complex Coastal Waters – A Case Study in the North. Sea, *Front. Mar. Sci.* 2020, 7, 1–16, doi: 10.3389/fmars.2020.00512.

Wollschläger J, Neale PJ, North RL, Striebel M & Zielinski O, Editorial: “Climate Change and Light in Aquatic Ecosystems: Variability & Ecological Consequences”, *Front. Mar. Sci.* 2021, doi: 10.3389/fmars.2021.688712.

SO301

Three-dimensional velocity structure of the 25°S Oceanic Core Complex and seismicity at the Rodriguez Triple Junction in the Central Indian Ocean

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

A. Dannowski, A. Jegen, L. Bitzan, D. Lange, O. Luecke, I. Grevenmeyer

Federal Institute for Geosciences and Natural Resources (BGR) | Hannover, Germany

M. Engels, M. Schnabel, B. Schramm, I. Heyde, U. Barckhausen, S. Ladage

Introduction

Three tectonic plates meet at the Rodriguez Triple Junction in the Central Indian Ocean. The plates are separated at different spreading rates (intermediate to ultra-slow) by the Central Indian Ridge (CIR), the South-East Indian Ridge (SEIR) and the South-West Indian Ridge (SWIR). The CIR appears to oscillate between opening mechanisms, associated either with magmatic or magma-starved spreading processes, which can be observed over a very confined stretch of crust. At ~25°S, west of the CIR an oceanic core complex (OCC) developed through a detachment fault that has lifted deep-seated rocks. It is situated in an unusual tectonic setting, since OCC's typically form at inside corner highs.

From November 2023 to January 2024, RV Sonne (SO301 - SCIROCCO) set out for a seismic reflection and 2D and 3D seismic refraction survey to provide a database for a better understanding of the tectonic setting and evolution of the area. A special focus was put on studying the structure and extent of the 25°S-OCC by placing ocean bottom seismometers (OBS) on top and around the OCC (yellow triangles in Figure 1). Prior to the cruise, from December 2019 to August 2020 an OBS network was deployed along the CIR, SWIR and at the northern tip of the SEIR (green triangles in Figure 1). The main reason for this long-term seismic network

was to understand the seismic behavior of the three distinct plate boundaries at a ridge-ridge-ridge triple junction. In this presentation we will focus on one 2D refraction seismic profile, the 3D active seismic OBS array and the passive seismic network.

Data and methods

The active seismic data focused on the oceanic core complex and the spreading centre of the Central Indian Ridge at the non-transform offset between the first and second CIR segments north of the RTJ (CIR-1 and CIR-2). The map in Figure 1 shows the experiment setup. The entire experiment comprises of 85 OBS deployments for active seismics. Thirty-three OBS were placed at a spacing of 5–6 km along an SW-NE transect, with a densified spacing on top of the OCC. The shot spacing was between 50–110 m. Further, a total of 35 stations was placed in a dense spacing of 2–8 km on top and around the OCC. As source served an array 16 G-guns with a total volume of ~51 liters operated at 150 bar. A 50 m shot interval was chosen for MCS shooting. The shot interval was changed to 60–65 s in curves and for all refraction seismic profiles (grey dots in Figure 1 indicate the density of shots recorded by the OBS). Using both, shots for the MCS and for seismic refraction enabled us to run a three-dimensional joint refraction and reflection travel time tomography. Separate inversions were run for P- and S-arrivals.

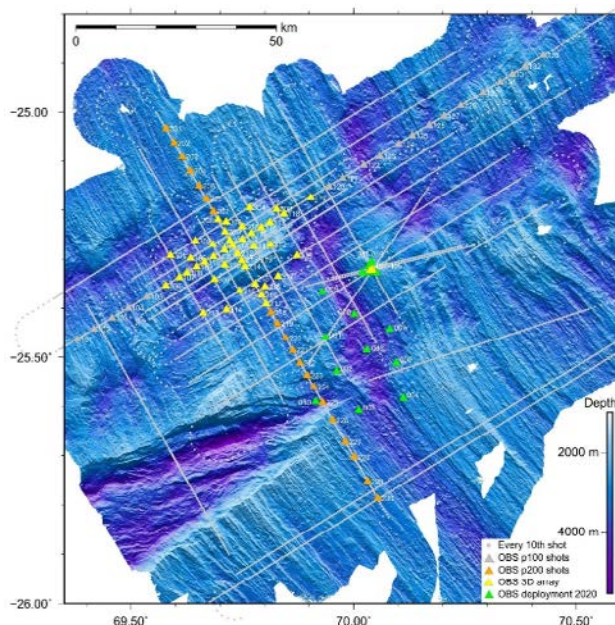


Figure 1: Extend of seafloor mapping during cruise SO301. In grey every 5th shot point is shown. The colored triangles mark the positions of the deployed OBS.

The passive seismic study focusses on the Rodriguez Triple Junction and on the Kairei hydrothermal vent field. Sixteen long-term OBS were deployed of which 10 instruments were broadband seismometers (Figure 1). Those stations recorded continuously for a period of 8 months, from 19 December 2019 to 9 August 2020 at a sampling frequency of 250 Hz. First, to account for the internal non-linear clock drift, cross-correlation was performed, using OBS06 as reference station. After the time correction of the data, standard methods in seismology were applied. These methods included a recently developed automatic signal detection and event association, followed by event location and magnitude estimation.

Results

Here we present preliminary results of the east-west trending 150 km long seismic refraction profile crossing the OCC and the CIR at the non-transfer offset between segments 1 and 2 of the CIR (CIR-1 and CIR-2, respectively). Clear crustal refracted P- and S-phases were observed to offsets of up to 40 km in the shot sections and mantle reflections could be identified sporadically. Preliminary results of the travel time tomographies along profile p100 indicate a strongly variable crustal construction, changing from magmatically robust crustal accretion and faulting dominated accommodation of the spreading. Highly fractured areas interchange with highly hydrated areas within short distances of ~20 km. A band of a high V_p/V_s ratio reaches down to 2 km below the seafloor at the OCC and locally on the India-Australian plate, indicating hydrated crust and possibly serpentinization.

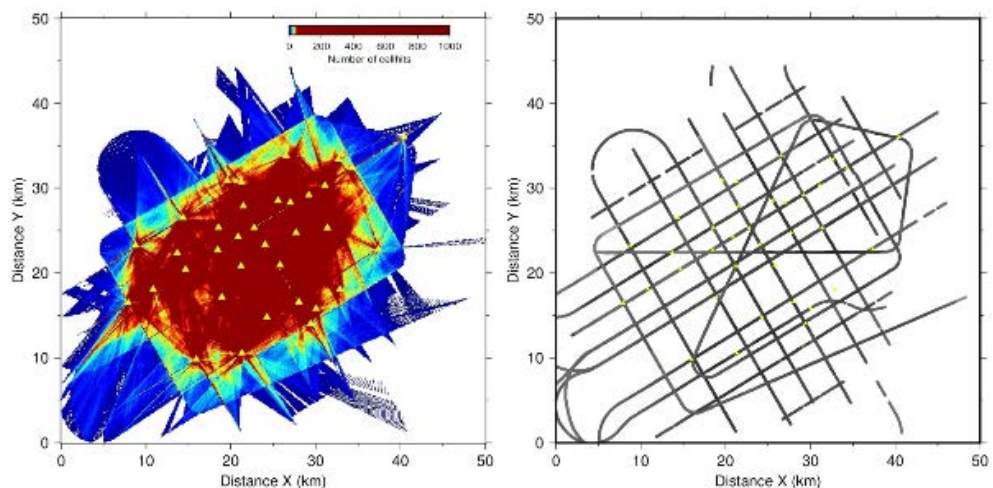


Figure 2: Left panel: ray coverage projected on a plane; yellow triangles mark all instruments used for 3D tomography. Right panel: pick locations used for the inversion.

The OCC shows a very good data coverage enabling a 3D travel time tomography (Figure 2). Preliminary results show elevated P-wave velocities in the core of the OCC indicating gabbro and mantle rocks at shallow levels. Velocities in east-west direction are highly variable, while they decrease towards the southern edge.

The seismicity study shows an asymmetric distribution of events, displaced relative to the central axes (Figure 3). While it is shifted to the north along the Southwest Indian Ridge, seismicity at the CIR occurs east of the axial valley. This 8-months observation is rather a snapshot of the Central Indian Ridge's and the Southwest Indian Ridge's current migration. However, the results indicate a successive migration of the triple junction northeastwards, with a successive plate relocation of the ridge axis, transferring crust between plates.

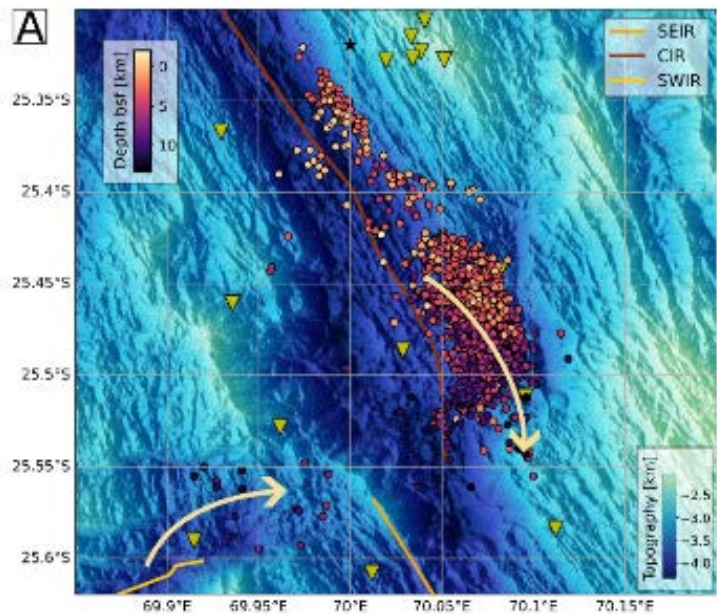


Figure 3: Event catalog, color coded according to depth below the seafloor. Yellow triangles mark the location of the OBS.

SO301

From Source to Sink: Complex Dual Role of the Kairei Hydrothermal Plume in Deep Ocean Trace Metal Cycling at the Central Indian Ridge.

– KABA (Ramifications of Venting at the Kairei Hydrothermal Field for Bathypelagic Microbial Processes in Consort With Carbon and Metal Cycling)

Authors

Constructor University | Bremen, Germany

N. Fröhberg, I. Pedre, A. Koschinsky

Federal Institute for Geosciences and Natural Resources (BGR) | Hannover, Germany

K. Schmidt, S. Fuchs

MARUM – Center for Marine Environmental Sciences, University of Bremen | Bremen, Germany

M. Walter, C. Kleint

Institute for Geosciences, Christian Albrechts University | Kiel, Germany

D. Garbe-Schönberg

Introduction and Objectives

During hydrothermal circulation, seawater penetrates fractures in oceanic crust where deep heat sources cause convection, with temperatures exceeding 400°C. The resulting fluids are highly enriched in metals leached from host rocks, including iron (Fe) and manganese (Mn) as well as cobalt (Co), copper (Cu), lead

(Pb), cadmium (Cd), nickel (Ni), and the rare earth elements & yttrium (REY). The hydrothermal flux of Fe to the ocean is estimated at 2.8×10^{10} mol/year compared to 2.3×10^{10} mol/year riverine fluxes (Alt, 2003). However, understanding processes affecting trace metals during transport in the buoyant and non-buoyant plume is crucial for quantification of hydrothermal metal fluxes to the ocean.

Study Area

The Kairei Hydrothermal Field (KHF) is located at the Central Indian Ridge at 25.32°S, 70.04°E and 2455 m depth (Hashimoto et al., 2001). This “magma-assisted, ultramafic-hosted” system has hydrothermal fluids with H_2 concentrations of 2.5–8.5 mmol/kg, approximately an order of magnitude higher than typical basalt-hosted systems. During research cruise SO301, we extensively mapped and sampled the vertically and horizontally spreading plume of hydrothermal material originating from the KHF to provide insight into the complex processes controlling the fate of hydrothermal trace metals during plume evolution with increasing distance from the vent.

Methods

We acquired samples using a trace metal rosette sampler (TMR) to avoid metal contamination. Since the TMR operates autonomously without a data connection during deployment, we mapped the plume of the KHF using the vessel's CTD rosette in tow-yo deployments (see Figure 1) and additionally took samples close to the vent field where high metal concentrations make contamination less of a concern. The TMR is constructed with a titanium frame and can support up to 12 5L water samplers. We deployed four externally sprung contamination-free samplers and eight metal-free “Niskin” samplers with internal latex springs. Plume tracking utilized MAPR sensors measuring turbidity as an indicator of particle load and oxidation-reduction-potential (ORP) anomaly caused by emission of reducing species (Baker, 1997).

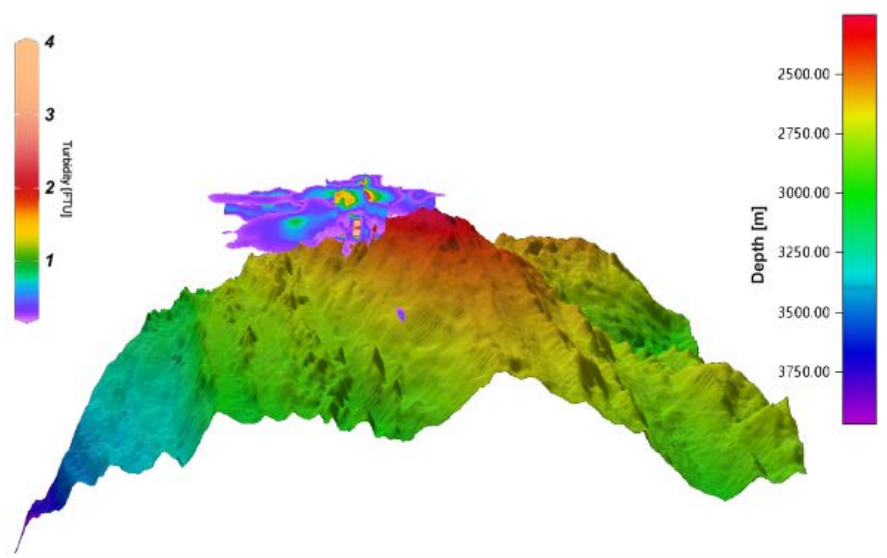


Figure 1: Three-dimensional view of the hydrothermal plume at Kairei by visualization of the turbidity signal measured during CTD-Tow-Yo deployments after background removal. The figure shows the view from the South of Hakuho Knoll with a 3.5x vertical exaggeration of depth and bathymetry.

We processed all samples in the onboard laboratory under filtered air using a class 1000 horizontal flow-bench. Most water samples were filtered by Acropak cartridge filters (0.2 μm PES) and selected samples were filtered sequentially with 0.8, 0.2, and 0.015 μm membrane filters. We determined total dissolved concentrations of trace metals using tandem ICP-MS/MS after automated online pre-concentration and matrix separation using SeaFAST SP2.

Results & Key Findings

Plume Source Elements: In the horizontally spreading non-buoyant plume, we measured dissolved concentrations of 890 nmol/kg Fe, 300 nmol/kg Mn, and 1.7 nmol/kg Co at station 23-TMR (see Figure 2) which showed the strongest hydrothermal influence. These concentrations represent a significant enrichment over background seawater concentrations for Co, Fe, Mn. But the plume concentrations only represent 0.00002 % of the endmember concentration for Fe, 0.000037 % for Mn, and 0.00021 % for Co (Gallant and Von Damm, 2006). While this highlights significantly faster precipitation and oxidation kinetics for Fe during mixing of the hot, reduced plume with cold oxic seawater, the opposite can be seen when comparing ratios during further mixing in the far-field with lower remaining concentrations for both Co and Mn compared to Fe. This indicates faster removal of Co and Mn or better stabilization of hydrothermal Fe in solution during far-field mixing (Sander & Koschinsky, 2011).

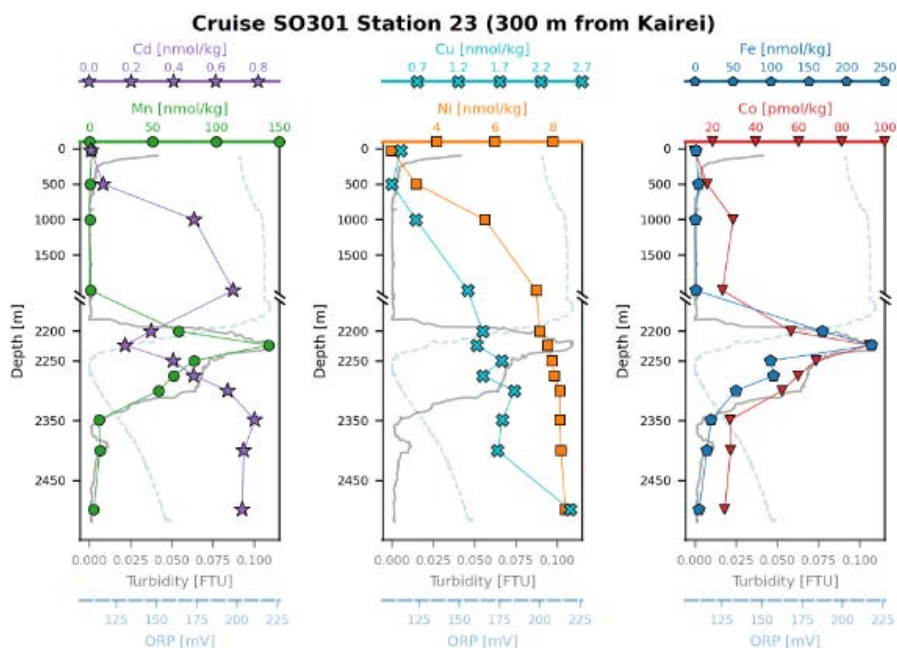


Figure 2: Selected depth profiles of trace metal concentrations in the water column at the Kairei hydrothermal field with turbidity and ORP data as tracers for hydrothermal input. The y-axis of all subplots is broken at 2150 m depth to magnify the hydrothermally affected zone of the water column.

Scavenged Elements: Both vanadium (V) and Cd are depleted compared to background. Vanadium is significantly depleted in both the source fluid and the hydrothermal plume, attributed to effective scavenging from the water column by Fe-oxide particle surfaces. Hydrothermally sourced iron oxides are estimated to remove 10–60% of the riverine V input to the ocean (Trefry and Metz, 1989). We observe significant depletion of Cd at the depth of the hydrothermal plume with near complete removal at station 23. While Metz and Trefry (1993) have suggested hydrothermal particles to be sources of Cd, our data shows near quantitative removal of background Cd in the plume making it a significant local sink. The REY show typical profiles for particle reactive elements with depletion at the depth of the hydrothermal plume, consistent with scavenging to mineral particle surfaces (Mitra et al., 1994).

Complex Behavior: Cu shows essentially the same profile as the background at station 23. Station 21, however, shows depletion of Cu at plume depth while we see enrichment at station 29. Removal of dissolved Cu to the particulate phase by precipitation of chalcopyrite and adsorption to particle surfaces is followed by release of Cu from sulphide transformation to oxides in the aging hydrothermal plume. Ni matches Cu behavior in the near-field with enrichment in the rising plume, background profile at station 23, and depletion at station 21. At further stations however, we see no significant hydrothermal impact on Ni concentrations.

Sequential filtration revealed significant size fractionation (see Figure 3) of Fe close to the vent source with large contributions of the particulate (0.2–0.8 μm) and large colloidal (0.015–0.2 μm) fractions to the total concentration. The larger size fractions are removed quickly in the vicinity of the vent field and play no significant role in the far-field plume as nanoparticles and organically complexed Fe is more stable in the non-buoyant plume. Manganese on the other side is present exclusively in the “truly dissolved fraction” (<0.015 μm) in these samples.

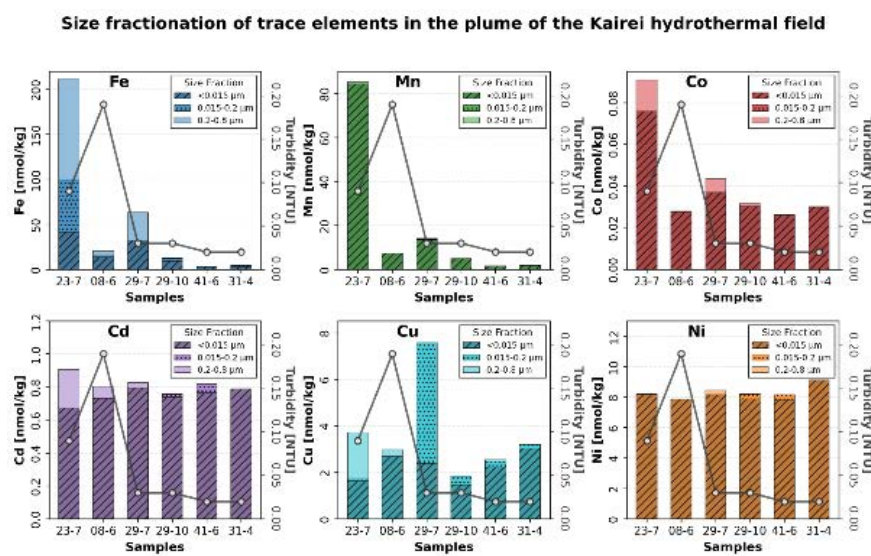


Figure 3: Stacked bar chart of the concentrations of trace metals in the size fractions <0.015 μm , 0.015–0.2 μm , and 0.2–0.8 μm acquired by sequential filtration of samples from the plume of the Kairei hydrothermal field during research cruise SO301 with increasing distance from the source going from left to right on the x-axis.

Implications

The data presented in this study reveal highly dynamic spreading of the Kairei hydrothermal plume coupled with complex geochemical processes affecting trace metals emitted with hydrothermal fluids. With sulphide minerals being a major pathway for removal of dissolved hydrothermal metals, the emission of H_2S by the hydrothermal fluid is one of the major controlling factors. At 3.9 mmol/kg H_2S , the Kairei endmember is rich in sulphide but also highly enriched in metals including 4.6 mmol/kg Fe creating a relatively high Fe/ H_2S ratio. While at systems with higher sulphide, precipitation can be expected to remove most dissolved metals early in plume mixing, the KHF fluids show relative excess of dissolved Fe and other metals. Therefore, we expect increased transport to the water column and higher importance of oxidation and organic complexation processes for transport of these elements.

The plume of the KHF is a local sink for REY from the water column, depleting the deep ocean of these elements despite the fluid having elevated concentrations. Consequently, we can expect significant deposition of REY alongside Fe/Mn deposits on the seafloor around the KHF. If Cd co-precipitation in formation of Fe-sulphides is common among hydrothermal plumes throughout the ocean, hydrothermal plumes could be a significant sink for the global Cd budget. For Ni, the Kairei plume is likely an overall net local sink as lower enrichment of dissolved Ni in the endmember is not sufficient to compensate for scavenging from the water column.

Conclusions

Our current understanding of plume processes is based largely on studies of early mixing in buoyant plumes with limited sample sets and low-resolution spatial coverage of non-buoyant plumes. High-resolution spatial mapping from meters to tens of kilometers reveals the KHF plume simultaneously acts as a source for Fe, Mn, Co, and potentially Cu to the deep ocean, while serving as a sink for V, Cd, Ni, and REY from ambient seawater. The magnitude and extent of these source/sink functions depend critically on endmember metal/sulfide ratios, organic complexation and plume dilution dynamics. The unexpected discovery of quantitative Cd removal and evidence for colloidal Fe transport mechanisms challenge current understanding of hydrothermal trace metal cycling. This complicates the interpretation of data with regards to source/sink estimations in order to quantify hydrothermal contributions to marine trace metal cycles. However, the high-resolution spatial coverage and multi-element approach demonstrated here provides a framework for capturing these complex, element-specific behaviors, enabling more accurate assessment of hydrothermal impacts on ocean biogeochemistry.

References

- Alt JC, Hydrothermal fluxes at mid-ocean ridges and on ridge flanks, *Comptes Rendus Geoscience* 2003, 335, 853-864, doi:10.1016/j.crte.2003.02.001.
- Baker ET, MAPR: A new instrument for hydrothermal plume mapping, *RIDGE Events* 1997, 8, 23-25.
- Gallant RM & Von Damm KL, Geochemical controls on hydrothermal fluids from the Kairei and Edmond Vent Fields, 23°-25°S, Central Indian Ridge, *Geochemistry, Geophysics, Geosystems* 2006, 7, Q06018, doi:10.1029/2005GC001067.

Gamo T, Nakayama E, Shitashima K, Isshiki K, et al., Hydrothermal plumes at the Rodriguez triple junction, Indian ridge, Earth and Planetary Science Letters 1996, 142, 261–270, doi:10.1016/0012-821X(96)00087-8.

Hashimoto J, Ohta S, Gamo T, Chiba H, et al., First Hydrothermal Vent Communities from the Indian Ocean Discovered, Zoological Science 2001, 18, 717–721, doi:10.2108/zsj.18.717.

Metz S & Trefry JH, Field and laboratory studies of metal uptake and release by hydrothermal precipitates, Journal of Geophysical Research: Solid Earth 1993, 98, 9661–9666, doi:10.1029/92JB00746.

Mitra A, Elderfield H & Greaves MJ, Rare earth elements in submarine hydrothermal fluids and plumes from the Mid-Atlantic Ridge, Marine Chemistry 1994, 46, 217–235, doi:10.1016/0304-4203(94)90079-5.

Sander SG & Koschinsky A, Metal flux from hydrothermal vents increased by organic complexation, Nature Geoscience 2011, 4, 145–150, doi:10.1038/ngeo1088.

Trefry JH & Metz S, Role of hydrothermal precipitates in the geochemical cycling of vanadium, Nature 1989, 342, 531–533, doi:10.1038/342531a0.

SO301

Seismic Velocity Structure and Segmentation of southwestern Somali Plate along the Central and Southwest Indian Ridges near the Rodrigues Triple Junction

Authors

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

O. Luecke, A. Dannowski, I. Grevemeyer

Federal Institute for Geosciences and Natural Resources (BGR) | Hannover, Germany

M. Engels, B. Schramm, I. Heyde, S. Ladage

Introduction

The Somali plate, a minor tectonic plate separated from the African plate by the East African Rift, is bound to the southwest by the Central Indian Ridge (CIR) and the Southwest Indian Ridge (SWIR) which, together with the Southeast Indian Ridge (SEIR), form the Rodrigues Triple Junction (RTJ). In this region (Figure 1), the Somali Plate is highly heterogeneous due to changes in spreading style from magmatic accretion to tectonic extension, and the segmentation of the CIR by means of non-transform discontinuities (Okino et al., 2015). One of the main features is the presence of the 25°S Oceanic Core Complex (OCC), contrasting with segments of the plate generated by magmatic accretion and the presence of ultramafic non-transform offset (NTO) massifs. The geology of the OCC and the NTO massifs is well documented by recovery of samples via dredges and submersible dives, and is described in Kumagai et al. (2008), Morishita et al. (2009), Sato et al. (2015), and Okino et al. (2015).

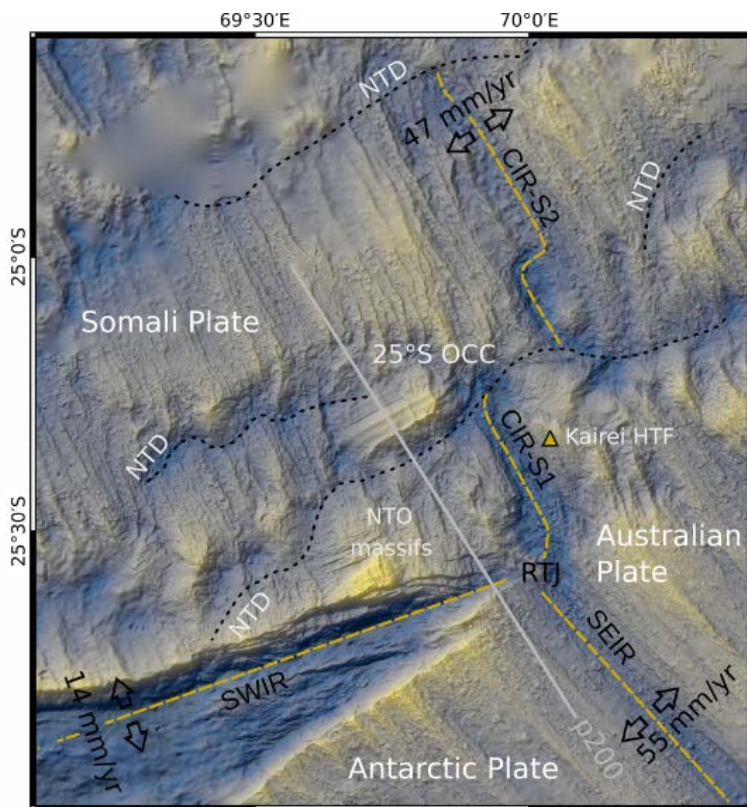


Figure 1: Bathymetry of the Rodrigues Triple Junction (RTJ) region. OCC: Oceanic Core-Complex; CIR: Central Indian Ridge; SEIR: Southeast Indian Ridge; SWIR: Southwest Indian Ridge; NTD: Non-Transform Discontinuity; NTO: Non-Transform Offset, HTF: Hydrothermal Field.

SO301 Cruise

The cruise SO301 was undertaken aboard the German research vessel Sonne, between November of 2023 and January of 2024. The main objective was the multi-method geophysical survey of the area of the RTJ with the adjacent 25°S OCC and the Kairei hydrothermal vent field within the research project SCIROCCO. The profile p200 extends for 104 km with a bearing of 330°. It crosses the Somali plate including the OCC and the NTO massifs as well as the SWIR and ends on the Antarctic plate. In total, 30 ocean bottom seismometers (OBS), equipped also with hydrophones, were deployed by free fall along the profile. Along p200, in addition to the seismic refraction profile, we acquired high-resolution bathymetry data as well as marine gravity data to support the interpretation of the velocity structure and perform joint inversion of seismic and gravimetric data. Additional data on a multi-channel seismic array was collected by the BGR using an 8 km long streamer.

Results from 2D Seismic Tomography

The NE-SW p200 profile provides information on the velocity structure and crustal thickness of two distinct domains of seafloor bounding the core complex to the south and north, as well as on the easternmost Southwest Indian Ridge segment and the Antarctic Plate.

A high P-wave velocity zone is present within the oceanic core complex, associated with gabbroic and ultramafic material bound by slower velocities indicating faulting and serpentinization of the shallow region, as well as possible scree deposits on the southern end. High crustal seismic velocities are present to the north and south of the core complex, associated with mafic and ultramafic non-transform offset massifs. The presence of these uplifted mantle materials is backed by results from joint seismic and gravity inversion which show high densities for the shallow regions within the high-velocity zones

The crust of the oceanic Somali Plate to the south and north of the core complex were generated at segments S1 and S2, respectively, of the Central Indian Ridge where magmatic accretion is dominant. The northern segment S2 shows a classical oceanic crust layer structure and well-defined wide-angle reflections from the Moho. The southern segment S1 is more heterogeneous with high velocities on the shallow part bounding the complex and poorly defined or absent PmP phases. The ultraslow spreading Southwest Indian Ridge axis shows characteristic high mantle velocities for the rifted valley and asymmetric ridge flanks.

The Antarctic plate, in contrast with the Somali plate, shows a typical layered structure toward the southeast, with a well-defined oceanic crust and velocities reaching 7.1 km/s at a depth of ~8 km below the sea surface. The structure of this plate reveals its formation through magmatic accretion processes at the Southeast Indian Ridge. This mode of origin is evident in the relatively uniform and layered composition observed within the plate, which is typical of crust generated in magmatically active ridge environments. In contrast, the Somali plate exhibits significant heterogeneity, with variations in crustal composition and structure resulting from a combination of magmatic accretion and tectonic extension. This distinction underscores the differences between the homogenous nature of the Antarctic plate crust formed at the Southeast Indian Ridge and the complex, segmented character of the Somali plate formed at the Central Indian Ridge.

Joint Density-Velocity Inversion

We performed a joint V_p seismic velocity and gravity data inversion to gain insights into the density structure of the crust and upper mantle. The joint inversion using

the code of Korenaga (2000) allows to reduce the non-uniqueness by integrating the velocity and gravity data and considers the physical relationship between these properties. The results from the joint inversion along p200 show lower densities ($\sim 2.7 \text{ g/cm}^3$) for the NW and SE shallow parts of the OCC. The centre part of the OCC shows densities of $2.9\text{--}3.0 \text{ g/cm}^3$ indicating the presence of gabbroic material in the shallow regions. The southeastern flank of the OCC shows high densities reaching up to 3.2 g/cm^3 supporting the interpretation of the presence of ultramafic material for this area associated with the non-transform offset massifs.

References

- Korenaga J, Holbrook WS, Kent GM, Kelemen PB, Detrick RS, Larsen HC, & Dahl-Jensen T, Crustal structure of the southeast Greenland margin from joint refraction and reflection seismic tomography, *Journal of Geophysical Research: Solid Earth* 2000, 105(B9), 21591–21614, doi:10.1029/2000jb900188.
- Kumagai H, Nakamura K, Toki T, Morishita T, Okino K, et al., Geological background of the Kaiei and Edmond hydrothermal fields along the Central Indian Ridge: Implications of their vent fluids' distinct chemistry, *Geofluids* 2008, 8(4), 239–251, doi:10.1111/j.1468-8123.2008.00223.x.
- Morishita T, Hara K, Nakamura K, Sawaguchi T, et al., Igneous, Alteration and Exhumation Processes Recorded in Abyssal Peridotites and Related Fault Rocks from an Oceanic Core Complex along the Central Indian Ridge, *Journal of Petrology* 2009, 50(7), 1299–1325, doi:10.1093/petrology/egp025.
- Okino K, Nakamura K, & Sato H, Tectonic Background of Four Hydrothermal Fields Along the Central Indian Ridge, In J.-i. Ishibashi, K. Okino, & M. Sunamura (Eds.), *Subseafloor Biosphere Linked to Hydrothermal Systems: TAIGA Concept* 2015, pp. 133–146, Springer Japan, doi:10.1007/978-4-431-54865-2_11.
- Sato H, Nakamura K, Kumagai H, Senda R, et al., Petrology and Geochemistry of Mid-Ocean Ridge Basalts from the Southern Central Indian Ridge, In J.-i. Ishibashi, K. Okino, & M. Sunamura (Eds.), *Subseafloor Biosphere Linked to Hydrothermal Systems: TAIGA Concept* 2015, pp. 163–175, Springer Japan, doi:10.1007/978-4-431-54865-2_13.

SO301

Methodical Perspectives on SO301 Seismic Data – a Case Study of the Kairei Hydrothermal Fluid Flow System

Authors

Federal Institute for Geosciences and Natural Resources (BGR) | Hannover, Germany

B. Schramm, M. Engels, M. Schnabel, T. Fridrich, H.-S. Hilbert, U. Barckhausen

GEOMAR Helmholtz Centre for Ocean Research Kiel | Kiel, Germany

A. Dannowski, O. Lücke

Seafloor massive sulphides (SMS), formed through hydrothermal vents at mid-ocean ridges and in volcanic areas, are a potential future source of critical metals. However, the ecological impact of mining on the deep-sea ecosystem is poorly constrained. A necessary first step for an estimation of the potential economic value of these deposits is imaging of their internal structure and active dynamic processes, since both characteristics may be highly variable at small scales. Particularly the imaging of the base of the SMS by geophysical methods - necessary for estimating the volume of massive sulphide - has been challenging in the past.

The in 2001 discovered Kairei hydrothermal field is located on the Central Indian Ridge (25.3° S, 70.0° E) and discharges H₂-rich hydrothermal fluids in a basalt hosted environment (Gamo et al., 2001; Hashimoto et al., 2001). The Kairei vent is located at a bench high in the stair-step morphology of the eastern rift-valley wall, with slope angles of 10° to 45° (Figure 1). The Kairei hydrothermal field is divided into an active and passive mound, which have a radius of approximately 100 to 200 m and are next to each other. Kairei is challenging to characterize due to its small-scale nature and setting in a complex tectonic environment.

In 2023, we collected geophysical data at the Kairei hydrothermal field during cruise SO301. Here we present multi-channel seismic (MCS) data and ocean bottom seismometer (OBS) data used to image the upper few hundred meters

below the seafloor at high resolution and to model the deep reaching fluid flow system. We show i) results of a downward continuation, a streamer tomography, ii) synthetic OBS seismic data in comparison with OBS reflections, and iii) a 3D seismic P-wave velocity model based on OBS data.

At water depths of over 2400 m, where slope angles are steep and the hydrothermal field is narrow, the OBS were deployed during cruise SO300/1 using video control and released just ~3 m above the seafloor. For the first time, BGR used a modified multifunction carriage for this purpose and placed the OBS (two stations per dive) precisely on the passive sulphide mound of Kairei. MCS data were recorded using a towed streamer with maximal offset of 7800 m. This was the first time that a streamer of this length was deployed on a German academic research vessel. The seismic G-gun source array had a volume of 51 liters, triggered every 50 m.

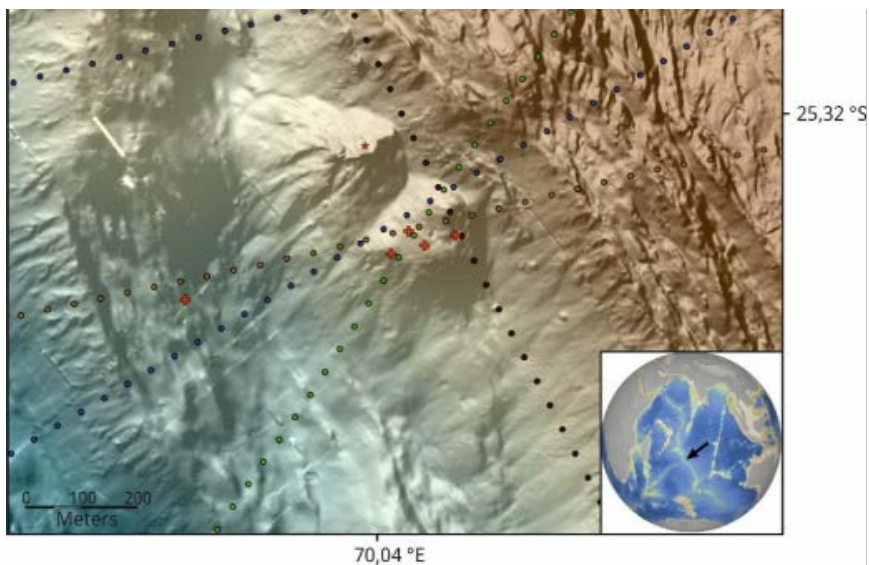


Figure1: Bathymetry map of the Kairei hydrothermal field (dots: seismic shot points; star: active mound; crosses: four OBS positions on passive mound plus one reference site).

We applied a technique suggested by Canales et al. (2012) that uses downward continuation of the wavefield by projecting a virtual configuration of sources and receivers down on the seafloor. This allows for the identification of refracted phases even at very small offsets. This method requires that the maximum offset within the data (streamer length) exceeds the water depth significantly. Therefore only a few examples of this kind of data evaluation exist for the deep ocean. For re-datuming the wavefield, we used the code DC from Jimenez-Tejero et al. (2022). On the resulting shot gathers, we identified first arrivals and performed velocity tomography. This resulted in a high-resolution P-wave velocity model covering

the uppermost 500 to 1000 m of the hydrothermal field. This method provides an exceptionally high coverage of rays.

We compared the streamer tomography results with the reflections of MCS data and the OBS data to identify the base of the sulfide mound. All three OBS components are compared in order to discuss the direction of the signal. As the images of the reflection waves are superimposed by side reflections, we additionally modelled synthetic OBS seismic data and compared it with the recorded OBS and MCS data.

To study the underlying fluid flow system, we modelled a 3D seismic refraction tomography of the Kairei field using OBS data. Our results image a zone of unusually high velocities starting 500 m below Kairei, indicating serpentinization and water circulation from a western ridge valley towards Kairei. Our improved imaging of the upper mound region demonstrates that the dynamics and the fluid flow circulation below the Kairei hydrothermal field are still complex.

Our findings highlight that only the combination and integration of multiple geophysical datasets enables the resolution required to investigate smaller areas of interest and to understand the complex geological processes active at Kairei. The tectonic setting of Kairei was particularly challenging. Other hydrothermal fields in a flatter setting would probably be an interesting target for further investigations in order to get an even sharper image of hydrothermal systems.

References

Canales JP, Carton H, Mutter JC, Harding A, Carbotte SM & Nedimović MR, Recent Advances in Multichannel Seismic Imaging for Academic Research in Deep Oceanic Environments. *Oceanography* 25 2012, 113–115, doi:10.5670/oceanog.2012.09.

Gamo T, Chiba H, Yamanaka T, Okudaira T, Hashimoto J, Tsuchida S, Ishibashi J-I, Kataoka S, Tsunogai U, Okamura K, Sano Y & Shinjo R, Chemical characteristics of newly discovered black smoker fluids and associated hydrothermal plumes at the Rodriguez Triple Junction, Central Indian Ridge, *Earth and Planetary Science Letters* 2012, 193(3–4), 371–379.

Hashimoto J, Ohta S, Gamo T, Chiba H, Yamaguchi T, Tsuchida S, Okudaira T, Watabe H, Yamanaka T & Kitazawa M, First hydrothermal vent communities from the Indian Ocean discovered, *Zoological science* 2001, 18(5), 717–721.

Jimenez-Tejero CE, Ranero CR, Sallares V & Gras C, Downward continuation of marine seismic reflection data: an undervalued tool to improve velocity models, *Geophysical Journal International* 2022, 230, 831–848, doi:10.1093/gji/ggac087.

Schriftenreihe Projektträger Jülich

1. Technologie- und Erkenntnistransfer aus der Wissenschaft in die Industrie Eine explorative Untersuchung in der deutschen Material- und Werkstoffforschung hrsg. von A. Pechmann, F. Piller und G. Schumacher (2010), 230 Seiten
ISBN: 978-3-89336-624-8
2. STATUSTAGUNG SCHIFFFAHRT UND MEERESTECHNIK
Tagungsband der Statustagung 2010 (2010), 173 Seiten
ISBN: 978-3-89336-677-4
3. STATUSTAGUNG SCHIFFFAHRT UND MEERESTECHNIK
Tagungsband der Statustagung 2011 (2011), 227 Seiten
ISBN: 978-3-89336-745-0
4. STATUSTAGUNG SCHIFFFAHRT UND MEERESTECHNIK
Tagungsband der Statustagung 2012 (2012), 206 Seiten
ISBN: 978-3-89336-832-7
5. STATUSTAGUNG MARITIME TECHNOLOGIEN
Tagungsband der Statustagung 2013 (2013), 188 Seiten
ISBN: 978-3-89336-922-5
6. STATUSTAGUNG MARITIME TECHNOLOGIEN
Tagungsband der Statustagung 2014 (2014), 179 Seiten
ISBN: 978-3-95806-006-7
7. STATUSTAGUNG MARITIME TECHNOLOGIEN
Tagungsband der Statustagung 2015 (2015), 196 Seiten
ISBN: 978-3-95806-104-0
8. STATUSTAGUNG MARITIME TECHNOLOGIEN
Tagungsband der Statustagung 2016 (2016), 220 Seiten
ISBN: 978-3-95806-187-3
9. STATUSSEMINAR MEERESFORSCHUNG mit FS SONNE
14.-15. Februar 2017 in Oldenburg – Tagungsband (2017), 221 Seiten
ISBN: 978-3-95806-207-8
10. STATUSTAGUNG MARITIME TECHNOLOGIEN
Tagungsband der Statustagung 2017 (2017), 224 Seiten
ISBN: 978-3-95806-277-1

11. STATUSTAGUNG MARITIME TECHNOLOGIEN
Tagungsband der Statustagung 2018 (2018), 224 Seiten
ISBN: 978-3-95806-366-2
12. STATUSTAGUNG MARITIME TECHNOLOGIEN
Tagungsband der Statustagung 2019 (2019), 187 Seiten
ISBN 978-3-95806-439-3
13. STATUS CONFERENCE RESEARCH VESSELS 2020
Conference transcript | Online-Publikation (2020), 409 Seiten
ISBN: 978-3-95806-479-9
14. STATUSTAGUNG MARITIME TECHNOLOGIEN
Tagungsband der Statustagung 2021 (2021), 289 Seiten
ISBN 978-3-95806-594-9
15. STATUS CONFERENCE RESEARCH VESSELS 2022
Conference transcript
Online-Publikation (2022), 476 Seiten
ISBN: 978-3-95806-608-3
16. STATUSTAGUNG MARITIME TECHNOLOGIEN
Tagungsband der Statustagung 2022 (2022), 285 Seiten
ISBN 978-3-95806-673-1
17. STATUSTAGUNG MARITIME TECHNOLOGIEN
Tagungsband der Statustagung 2023 (2023), 275 Seiten
ISBN 978-3-95806-732-5
18. STATUS CONFERENCE RESEARCH VESSELS 2024
Conference transcript, Online-Publikation (2024), 574 Seiten
ISBN: 973-3-95806-747-9
19. STATUSTAGUNG MARITIME TECHNOLOGIEN
Tagungsband der Statustagung 2024 (2024), 313 Seiten
ISBN 978-3-95806-798-1
20. STATUSTAGUNG MARITIME TECHNOLOGIEN
Tagungsband der Statustagung 2025 (2025), 423 Seiten
ISBN 978-3-95806-873-5
21. Status Conference Research Vessels 2026
Conference transcript, Online-Publikation (2026), 909 Seiten
ISBN: 973-3-95806-890-2