Observations of Hydraulic and Transport „Skin Effects“

SKB Task Force Workshop
Prague 2016

GRS - 504

Gesellschaft für Anlagen-
und Reaktorsicherheit
(GRS) gGmbH

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Klaus-Peter Kröhn (editor)
Bill Lanyon (editor)

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- Peter Andersson, Geosigma, Sweden
- Johan Byegård, Geosigma, Sweden
- Bill Dershowitz, for Japan Atomic Energy Agency/Golder
- Stefan Finsterle, Energy Geosciences Division, Lawrence Berkeley National Labor-atory, USA
- Jerker Jarsjö, Stockholm University, Department of Physical Geography, Sweden
- Martin Löfgren, Niressa, Sweden
- Mansueto Morosini, SKB, Sweden
- Ivars Neretnieks, Royal Institute of Technology (KTH), Sweden
- Kersti Nilsson, Geosigma, Sweden
- Josep M. Soler, IDAEA-CSIC, Spain
- Yukio Tachi, Japan Atomic Energy Agency (JAEA), Japan
- Ryuji Takeuchi, Japan Atomic Energy Agency (JAEA), Tono, Japan

Abstract

This report provides a synthesis of the contributions and subsequent discussions at the SKB Task Force (GWFTS) “Skin Workshop” held as part of Task Force Meeting #34, in Prague, 9-12th May 2016. It has been produced to provide a database of relevant observations regarding the “skin effect”. For the purposes of the workshop the suggested definition for “skin effect” was:

A reduction of flow or diffusive solute transport in the immediate vicinity of tunnels and boreholes in crystalline rock (also called “geotechnical openings”) as a consequence of excavation and drilling, respectively.

We have split the material presented into flow-related and transport-related observations. For the most part flow observations relate to reduced flow in fracture systems, while transport observations relate to differences in diffusivity or sorption in the rock matrix. Within this document we have further classified observations according to spatial scale and temporal scale.

In bringing these observations together we hope to spread awareness of skin effects and the existing literature concerning them.

Table of content

1 Introduction

1.1 The GWFTS Task Force

The SKB Task Force on Modelling of Groundwater Flow and Transport of Solutes is a forum for international organisations to interact in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock. Emphasis is put on building confidence in the approaches and methods in use for modelling of groundwater flow and solute transport in order to demonstrate their use for performance and safety assessments. Svensk Kärnbränslehantering AB (SKB) established the Task Force in 1992 to support the Äspö Hard Rock Laboratory.

The overall objective of the Task Force is “to increase the understanding of the processes that govern retention (retention here refers to both reversible and irreversible immobilisation processes) of radionuclides transported in crystalline rock and to increase the credibility in the computer models used for groundwater flow and radionuclide transport” /GUS 09/.

The Task Force organises its work around well-defined tasks considering specific aspects of flow and transport in fractured rock. Recent tasks include:

- Task 7 - Long-term pumping tests at Olkiluoto
- Task 8 - Modelling of the Bentonite Rock Interaction Experiment (BRIE) at Äspö
- Task 9 - Modelling the REPRO, and LTDE-SD experiments at Olkiluoto and Äspö, respectively

Task 8 is currently concluding and Task 9 is in progress. The topic of “skin-effect” around tunnels and boreholes had arisen in discussions concerning both Task 8 and 9. On the one hand, implementing a “skin” term in numerical models helped considerably in reproducing measurements. But on the other hand the nature of the “skin” remained unclear as there were several plausible but not substantiated explanations. Following further discussions at Task Force Meeting #33 in Kalmar in October 2015, it was decided to include a Workshop on Skin Effect at the next Task Force Meeting #34 held in Prague 9-12th May 2016. The aim was to make a synthesis using the expertise and experience within the Task Force. Contributions in the form of short presentations of relevant experience (observations/case histories or theoretical/modelling contributions) were to be documented as short abstracts. A short briefing note was sent out to all participants to provide background to the workshop. This report provides a synthesis of the contributions and subsequent discussions. It has been produced to provide a database of relevant observations regarding “skin effects”.

For the purposes of the workshop the suggested definition for “skin effect” was:

A reduction of flow or diffusive solute transport in the immediate vicinity of tunnels and boreholes in crystalline rock (also called “geotechnical openings”) as a consequence of excavation and drilling, respectively.[1]

This is in contradiction with observed increases in permeability and porosity due to the creation of an Excavation Damage Zone (EDZ) or Borehole Damage Zone (BDZ) by the excavation or drilling process (see /TSA 05/ and /BÄC 08/).

As the concept of skin typically requires a relative reduction in permeability, it is also important to identify the benchmark values used to identify this reduction. Typically these are either relative to far-field values (where the properties or performance of the skin zone are compared with values from further away from the borehole or excavation) or to prior or early-time values (when a skin develops and results in a reduction in permeability or transport property compared to the prior value).

1.2 Background

1.2.1 Early work on the skin effect in wellbores

The concept of a near-wellbore skin effect has been widely used in the hydrocarbon industry since the 1950s. Skin effects around wellbores have been ascribed to a range of processes:

- Damage to the rock formation due to drilling mud invasion (see abstract of Löfgren);

[1] In fact some of the transport observations relate to enhanced solute transport in the borehole nearfield.

– Poor casing perforation (location and frequency of perforation);
– Non-Darcy flow (particularly in gas wells /RAM 64/);
– Small-scale near-borehole heterogeneity.

In order to quantify near-wellbore flow resistance, /VAN 53/ and /HUR 53/ relate a near-wellbore resistance (of infinitesimal thickness) due to drilling, completion and production techniques to a parameter S (dimensionless pressure drop per unit rate) and provide methods for computing S from analysis of pressure build-up curves. Subsequently /EAR 77/ developed an approach based on a skin zone of finite thickness where the skin factor is defined as:

$$\zeta = \left({}^{K}/_{K_s} - 1 \right) \ln\left({}^{r_s}/_{r_w} \right) \tag{1.1}$$

Resulting in the well having an “effective radius” of

$$r_{w,effective} = r_w \, e^{-\zeta} \tag{1.2}$$

where ζ is the skin factor;

K and K_s are the hydraulic conductivity (or permeability) of the formation and skin zone;

r_w and r_s are the radii of the well and skin zone; and

$r_{w,effective}$ is the effective radius of the well accounting for the skin zone.

Note that ζ can be both positive: indicating a near-wellbore pressure drop and restriction to flow; or negative indicating a more permeable near-wellbore region (negative skin is not the focus of this report). Negative skins are often associated with hydrofracturing or natural fractures.

Various interventions are possible if skin results in poor well performance. /VAN 53/ suggests methods for countering the effect in production wells (reperforating and acidizing).

1.2.2 Skin effect in deep mines in crystalline rock

While the concept of near-wellbore skin was widely understood, results from the Stripa URL in Sweden in the 1980s /GAL 83/ and 1990s highlighted possible skin effects around tunnels in crystalline rock /LON 95/. In particular, two large-scale experiments showed strong skin effects limiting inflow to tunnels.

The Macropermeability experiment was a ventilation test performed at the Stripa Mine in Sweden. The groundwater inflow to a 33 m long drift was measured together with the pressure in 64 packer-intervals in 10 boreholes around the drift. /PUS 03/ comment that "Stress-induced reduction of the radial [hydraulic conductivity] K to 4E-11 m/s, i. e. a skin effect, was found for the surrounding 3 m thick annulus." A subsequent "Macroflow Test" indicated increased flow (compared to the expectation for undisturbed rock) axial to the tunnel of a factor of 100 /PUS 89/, /PUS 03/.

Measurements from the Stripa SDE and Validation Drift experiments (within the Site Characterisation and Validation SCV Block) allow inflows to a 100 m long array of six boreholes to be compared with the inflow to a tunnel excavated along the first 50 m of the borehole array /OLS 92/. Inflow to the tunnel was estimated to be ~12% of the inflow to the equivalent sections of the borehole array. Several groups (/DER 92/, /HER 92/, /BAR 92/ explored the possible influence of stress-coupled deformation while /BLA 16/ discusses these results and interprets them in terms of "sparse channel networks".

1.3 Report structure

We have split the material presented into flow-related (Chapter 2) and transport-related observations (Chapter 3). For the most part flow observations relate to reduced flow in fracture systems, while transport observations relate to differences in diffusivity or sorption in the rock matrix. Within this document we have further classified observations according to spatial scale and temporal scale. The scale of transport observations is typically well defined in core tests, whereas spatial scales for the flow observations are more approximate and we have used the following semi-quantitative scale: core or borehole ~0.01 – 0.1 m, tunnel 1 – 10 m and repository > 10 – 100 m.

Synthesis of the observations are included at the end of Chapters 2 and 3 and conclusions provided in Chapter 4. Some additional analyses are provided as appendices.

2 Flow skin processes

2.1 Observations

The observations below are those presented by the participants in the Skin Workshop (or subsequently submitted) during Task Force Meeting #34. Observations concerning a flow skin have been made at the borehole, tunnel and repository scale. The next subsections are arranged in increasing spatial scale. Contributions to the skin workshop are denoted by a bold headline indicating the topic followed by the contributor in plain *italics*. A summary of the observations is given in Tab. 2.1.

2.1.1 Borehole scale

The skin effect – an established fact in wells in sedimentary rock

Martin Löfgren, Niressa, Sweden

Wells are routinely drilled into sedimentary rock to extract water and hydrocarbons. In this field the skin effect is an established fact and is mainly attributed to formation damage. The formation damage may have been mechanically induced in the drilling by the drill bit. Fines in the drilling fluid may also clogs the pores. “Long-term” formation damage may be induced by swelling clays. Clays may swell upon changed groundwater chemistry and hence reduced the pore apertures. More importantly the outer layers of swelling clays may peel off and be transported to constrictions where clogging may occur. In granitic rock, such clays are present as fracture minerals and as weathering products in altered, fracture adjacent rock. Unaltered sheet silicates also constitute a substantial part of the rock matrix (e. g. biotite).

Well testing for skin effects in fractured rock

Mansueto Morosini, SKB, Sweden

Encountering excessively high values of skin (i. e. near-wellbore flow resistance) and a discrepancy between transmissivities derived from drawdown and build-up phase lead us to suspect additional well loss components are present. A suite of well tests are undertaken at -400 masl (metres above sea level) on fractures with aperture.

Tab. 2.1 Tabular summary of observations

Topic	Material	Location	Spatial scale	Temporal scale	"Skin depth"	Process(es)	Observation	Source
Äspö well testing skin	Äspö granite	Äspö, Sweden	Borehole	Typical test duration of hours	Unknown	Stress-dependent aperture (injection vs withdrawal) Turbulent (non-Darcy) flow Two-phase flow (not addressed in testing)	Reduction in flow between injection and withdrawal tests and skin due to turbulent flow	Presentation Morosini
Äspö degassing tests	Äspö granite	Äspö, Sweden	Borehole	Test durations of hours to 10s of hours	Analytical estimates but no measurement	Two-phase flow and groundwater degassing Turbulent flow, fracture deformation	Reduction of borehole inflow due to degassing of groundwater	/JAR 97/ /JAR 00/
Macropermeability Test	Stripa granite	Stripa, Sweden	Tunnel	Flow period duration ~2 days	1-3m	Hydromechanical closure of fractures Heterogeneity and channelling	Increased pressure gradient close to excavation	/PUS 03/ /BLA 16/
Äspö Two-phase Flow experiment	Äspö granite	Äspö, Sweden	Tunnel	Pressure measurements over 10s of days	<1m	Two-phase flow	Increased pressure gradient close to excavation	/KUL 02/
SDE/SCV Experiment	Stripa granite	Stripa, Sweden	Tunnel	Inflow measurements over 10s of days	Unknown	Two-phase flow Fracture-sealing due to precipitation Hydromechanical closure of fractures Heterogeneity and channelling	Inflow reduction relative to equivalent borehole array	/BAR 92/, /DER 92/, /HER 92/, /LON 95/, /BLA 16/

Topic	Material	Location	Spatial scale	Temporal scale	"Skin depth"	Process(es)	Observation	Source
GTS Nearfield	Grimsel garnodiorite/ Central Aare granite	GTS, Switzerland	Tunnel	Long-term inflow over years	Partially saturated zone may extend several metres into matrix	Two-phase flow and channelling	Highly localised inflows to tunnels due to desaturation of the rock matrix due to ventilation	/MAR 99/
Room 209 fracture	Lac Du Bonnet Granite	AECL URL, Pinnawa, Canada	Tunnel	During excavation	1-2m	Shear-induced closure of fractures	Reduction in transmissivity during excavation	/LAN 91/ /TAN 93/
YMP ECRB Cross Drift and Niche 5	Lower lithophysal welded tuff	Yucca Mountain, Nevada, USA	Tunnel	Seepage measurements over 10s of days	Unknown	Evaporation and seepage in partially saturated rock	Reduced seepage into excavation due to diversion and evaporation	/GHE 04/
MIU Ventilation Shaft	Toki granite	Mizunami, Japan	Tunnel	Head gradient around shaft	<10m	Effect of shotcrete and shaft excavation	High pressure gradient around shaft	/TAK 10/
SFR flow reduction	Fine medium-grained meta-granodiorite, pegmatitic granite and pegmatite	SFR Forsmark, Sweden	Repository	Over 30yrs	Ongoing pressure drop observed in boreholes extending 10s of meters from tunnels	Two-phase flow Clogging with fine material Fracture-sealing due to precipitation Hydromechanical closure of fractures Heterogeneity and compartmentalisation	Ongoing decline in inflow to tunnels over 30+years	/OHM 13/

0.5 – 1 mm in granitic rock to investigate the effect of turbulent flow and stress induced fracture aperture changes on the derived skin and transmissivity values. Preliminary results show there is a clear and large effect due to turbulent flow and that consistent transmissivities are obtained when the turbulent flow component is included. With regard to stress/aperture effects we could establish that there is a clear reduction in specific capacity with increasing injection pressure. This would indicate a reduction of fracture aperture through strike/slip movement and/or turbulent flow component. The aperture reduction appears irreversible. Additionally, we could also establish that for same ΔP (pressure perturbation) and Δt (test duration) injection gives twice as high a specific capacity as withdrawal.

The Äspö degassing tests

Jerker Jarsjö, Stockholm University, Department of Physical Geography, Sweden

A series of "degassing tests" were performed at the Äspö HRL (/GEL 95/, /JAR 00/). The first series of tests were performed as a series of single-well borehole tests at 300 m depth below sea level, in which a single fracture with a transmissivity of approximately 10^{-6} m^2/s was tested. The gas contents[2] of the formation water at atmospheric pressure conditions ranged between 0.1 % and 5 % (/GEL 95/). Although there was a considerable variability in gas contents, they exceed the solubility limit at atmospheric pressure most of the time, implying that degassing would occur if the test hole pressure were to be lowered to atmospheric pressure. In a first test stage, the test hole pressure was successively lowered below formation pressure, but kept above the bubble-pressure of the gas dissolved in the formation water. Results showed an expected linear relation between the borehole pressure and flowrate. In a second test stage, the test hole pressure was reduced to atmospheric pressure (below the gas bubble pressure), while observing whether or not degassing effects would cause deviations from the linear pressure-flowrate relation. No such deviations were seen, implying that degassing would not cause inflow reductions to boreholes at natural conditions.

[2] Gas content is expressed as the percent volume of gas per volume of water corrected to standard temperature and pressure that evolves when the liquid pressure is lowered.

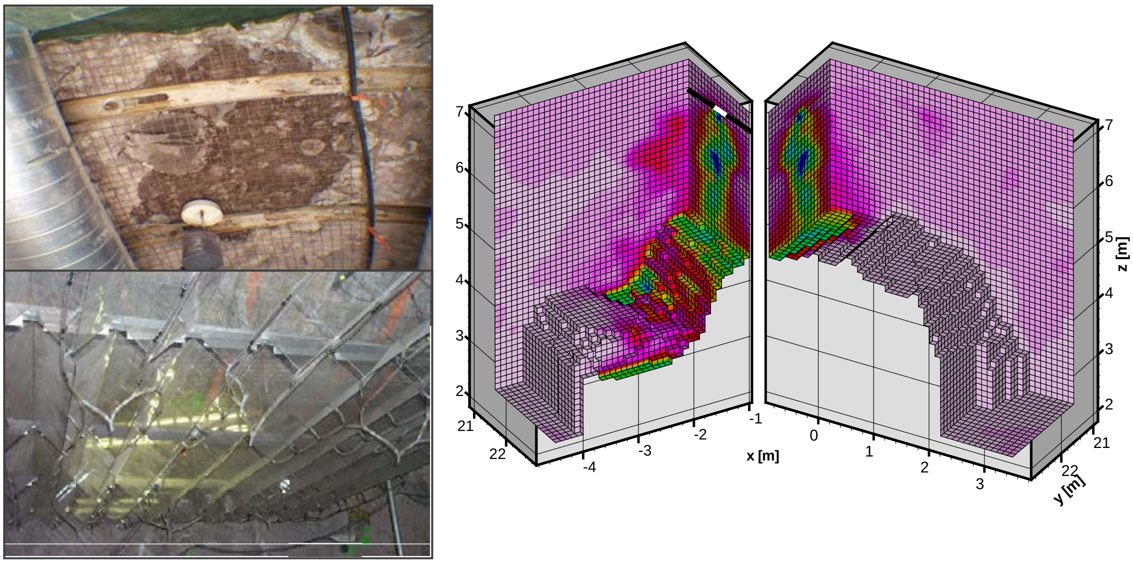
In a series of follow-up experiments (/JAR 00/), additional single-well tests were performed at the Äspö HRL at 450 m depth. Results showed that the borehole pressures exhibited a linear relation with the steady-state flowrates down to atmospheric pressure, confirming the lack of degassing effects in boreholes at natural conditions. However, a series of dipole experiment were also conducted, where formation gas contents were elevated to 13.0 ± 1.8 % throughout the experiment (/JAR 97/, /JAR 00/) by injecting gas (N_2) saturated water in a borehole located near (1 – 2 m) the degassing tests hole. In this case, clear deviations from the linear borehole pressure-flowrate relation were seen as the borehole pressure was lowered below the gas bubble pressure. This indicates that degassing may cause borehole inflow reductions if gas contents are above some critical threshold value (which appears to be on the order of 10 % for boreholes). Due to effects of geometry and boundary conditions, this threshold gas content may however be lower for inflow to tunnels (drifts). Consequently, modelling results show that degassing effects may contribute to inflow reductions to tunnels at natural gas contents (2 – 5 %), in particular in presence of hysteresis effects (/JAR 01/).

2.1.2 Tunnel scale

Capillary and Evaporation Barriers

Stefan Finsterle, Energy Geosciences Division, Lawrence Berkeley National Laboratory, USA

Under unsaturated conditions, an open tunnel or borehole acts as a capillary barrier, diverting flow around the opening due to capillarity acting in both the fractures and the rock matrix. The local percolation flux arriving at the opening has to exceed a certain threshold value before dripping is initiated. In addition, seepage rates may be reduced due to evaporation at the wall of the opening. The combined effect of capillary diversion and evaporation in reducing measurable inflows into an opening has been studied experimentally and through numerical modeling at the Yucca Mountain site. Details about these analyses can be found in /GHE 04/ and the references cited therein.



(a) (b)

Fig. 2.1 (a) Liquid-release test at Yucca Mountain and (b) related numerical analysis to study capillary-barrier and evaporation effects on drift seepage

Near-tunnel conditions at the Grimsel Test Site (GTS)

Bill Lanyon, Fracture Systems Ltd, UK

The GTS is located at approximately 1750 masl in the fractured crystalline rock of the central Aare Massif, 450 m below the eastern flank of the Juchlistock mountain. The underground laboratory was excavated by TBM in 1983-4 and is operated by Nagra.

During the winter the dry air (75 – 80 %RH) results in significant desaturation of the rock matrix and lower permeability structures (shear zones and lamprophyre dykes). This partially saturated zone can extend several metres into the side-wall of the laboratory tunnels /MAR 99/. More permeable features (typically brittle fracturing associated with shear zones and lamprophyre dykes) show as “wet-spots”.

Flow in the southern part of the GTS largely occurs in networks of channels in brittle fractures associated with a series of ductile shear zones. These channels are highly heterogeneous in both form and hydraulic properties. Strong variability is seen in tunnel inflows (both between and around tunnels) and in hydraulic tests. Close to the tunnel wall this variability may be emphasised by desaturation of low permeability parts of transmissive structures resulting in highly channellised inflow points around the tunnels.

Fig. 2.2 Damp spots on fractures in lamprophyre (metabasic dyke)

Indications of a flow impeding skin from the two-phase flow test at Äspö

Klaus-Peter Kröhn, GRS, Germany

During the years 1997 to 1999 the Two-Phase Flow Experiment was jointly performed with BGR at the Hard Rock Laboratory at Äspö /KUL 02/. It was located at niche 2715 on the 360 m level. The objective was to perform a dipole test with gas injection and extraction at two different locations in the V2-fracture that is crossing the niche. Groundwork for the experiment was laid with respect to site preparation and hydrogeological characterization of the undisturbed single-phase flow field. The initially highly damaged front face of the niche was removed by smooth blasting to reduce the size of the EDZ. The V2-fracture was assumed to be hydraulically connected to a sub-vertical swarm of fractures that reached the surface.

An array of 22 probing boreholes was drilled from the niche into the rock, eight of them crossing the V2-fracture and allowing measurements of the hydraulic pressure up to a depth of about 5 m from the niche face. Monitoring the pressure at these eight locations showed that the hydraulic pathways in the V2-fracture were well connected. All pressure transducers in the fracture responded fairly quickly to disturbances in the flow. Also recovery from these disturbances was fast. Plotting the measured pressure values as a function of the distance from the niche face revealed a sharp pressure gradient within the first metre from the niche face followed by a plateau of about 1.8 MPa that was found to reach the maximum distance of 5 m.

The phenomenon was not known at GRS and also discussions with BGR and SKB produced no indications of a “skin-effect”. Interpretation was thus only restricted to “… the assumption of a narrow zone – probably less than one metre in thickness – surrounding the niche. This zone would have to be hydraulically much tighter than the neighbouring area.” Up to now no more detailed explanations have been found though strong candidates appear to be either “degassing”, “mechanical closure of the fracture“ or “clogging from blasting“.

Geomechanical Mechanism of Borehole and Tunnel Skin

Japan Atomic Energy Agency/Golder - Bill Dershowitz (Golder)

Well theory finds that for both confined and unconfined aquifers, water inflow increases as a function of the radius squared. Hence, water supply and oil wells are installed with large radii to achieve desired flow rates. However, at the scale of waste repository tunnels and caverns, observed inflows can frequently be less than that from even a single low diameter pilot well. A range of theories have been advanced to explain this phenomenon. The JAEA/Golder presentation focused on geomechanical mechanisms related primarily to stress redistribution. JAEA/Golder presented examples of how stress redistribution has different effects at different locations around an excavation, both opening and closing fractures through hydromechanical coupling. The net effect of stress redistribution therefore depends on the local fracture orientations, fracture roughness and microstructure, and nuances of the pre-existing stress field magnitudes and orientations. Both stress concentration and stress-shadow regions are formed, and fracture transmissivity can increase or decrease in each of these zones, depending on local conditions of shear and tension. Since most water pressure drop occurs very close to the tunnel wall, it is reasonable to assume that the stress redistribution in this zone may have a significant effect on inflow rates and patterns.

JAEA/Golder presented examples of stress redistribution around a tunnel and emplacement hole, and the consequent change in the normal and shear stress on fractures. JAEA/Golder presented analytical solutions relating fracture roughness, stress, and shear dilation, and normal effective stress and normal dilation.

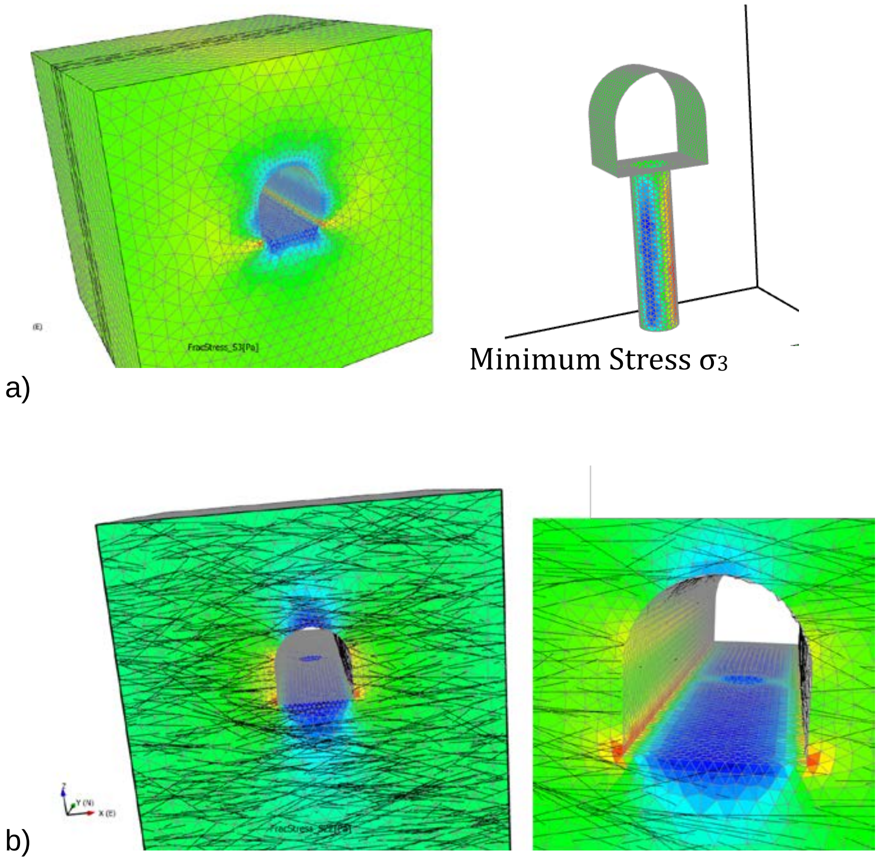


Fig. 2.3 Stress redistribution around excavations: a) computed minimum stress and shear stresses on excavation and deposition hole surface; b) fracture network and vertical Stress σ_{zz} and maximum principal stress σ_1

Transmissivity reduction during excavation in Room 209 at the AECL URL[3]

/TAN 93/ describe a reduction in fracture zone transmissivity during an excavation response experiment at the URL /LAN 91/. Transmissivity decreased as the “pilot”&”slash” “faces” passed through the fracture zone. Transmissivity then increased towards pre-excavation values as the face passed the fracture zone. /LAN 91/ comment that “detailed pressure measurements recorded during the excavation of the fracture plane also reveal that a sudden increase in hydraulic pressure occurred at the moment the intersecting excavation round was removed. This indicates a decrease in seepage,

[3] This example was included in the briefing note for the workshop, but not presented at the workshop.

and therefore supports the other evidence that a decrease in hydraulic aperture had occurred."

The Room 209 fracture is a near vertical planar water conducting facture in otherwise unfractured rock. The fracture runs approximately perpendicular to the excavation and a composite structure made up of 5 discontinuous fractures in a 0.4m-wide zone. The zone is connected to a larger structure (Facture Zone 2.5) about 30 m above the excavation. The test was monitored with extensometers, strain cells, a sliding micrometer and piezometers as shown in Fig. 2.4. It was not possible to reproduce the observed responses by assuming normal-stress dependent opening/closure however 3D finite element models including transmissivity reduction due to shear displacements in the zone were able to reproduce the observations. The authors comment that "only shear displacements that cut off flow channels in the fracture zone seem to provide the necessary mechanism for generating high pressure gradients."

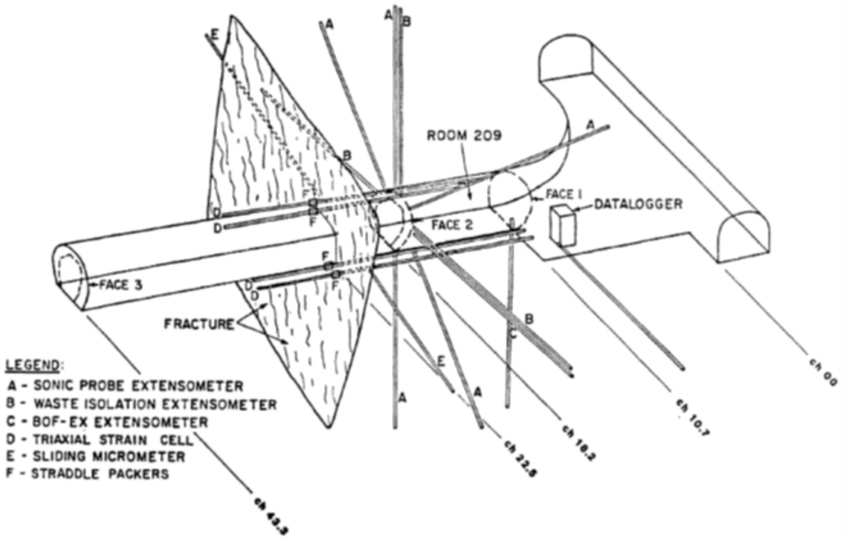


Fig. 2.4 Isometric View of the Instrumentation Arrangement in the Room 209 Instrument Array from /LAN 91/

Skin zone effects – TBD! Some experiences from performing flow and transport experiments in skin zones[4]

Peter Andersson, Geosigma, Sweden

In the Stripa mine, a large-scale experiment, the "Site Characterization and Validation Experiment" (SCV) was performed in the late 80´s. The experiment included drilling of six boreholes, 100 m long (D-holes), in which extensive hydraulic testing was performed. Pressure was released in steps in all six boreholes where the last step should represent the conditions of an open drift. The first 50 meters of the borehole length was the excavated and inflow to the drift was monitored in plastic sheets and short boreholes in the bottom of the drift. Transport properties were also determined by performing tracer tests in a fracture zone intersecting the drift before and after excavation. The resulting inflow to the drift was found to be only about 12 % of the inflow to the 6 boreholes. The inflow to the inner part of the boreholes (not excavated) was also reduced by 50 %. The latter observation indicates that skin effects may have longer influence distances than just a few meters from the drift.

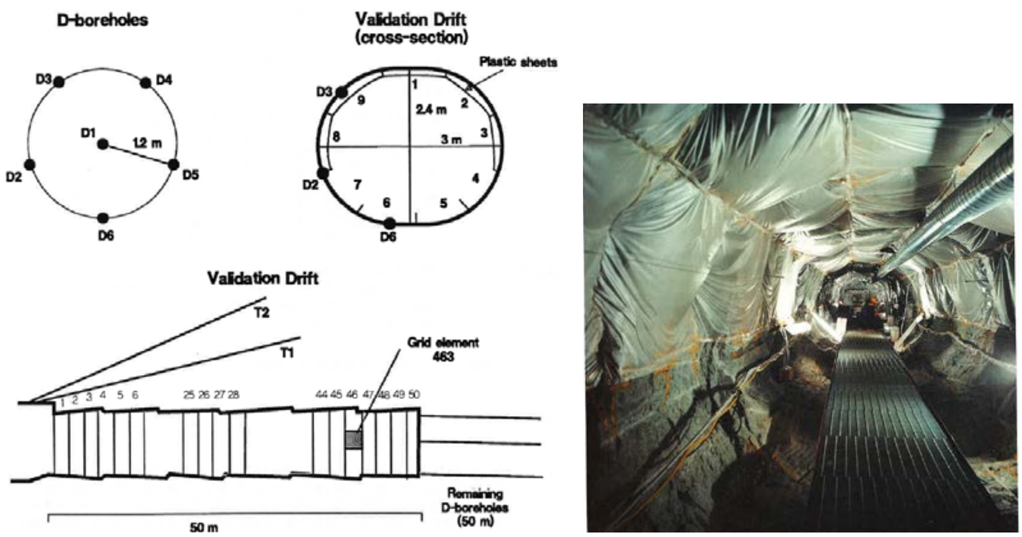


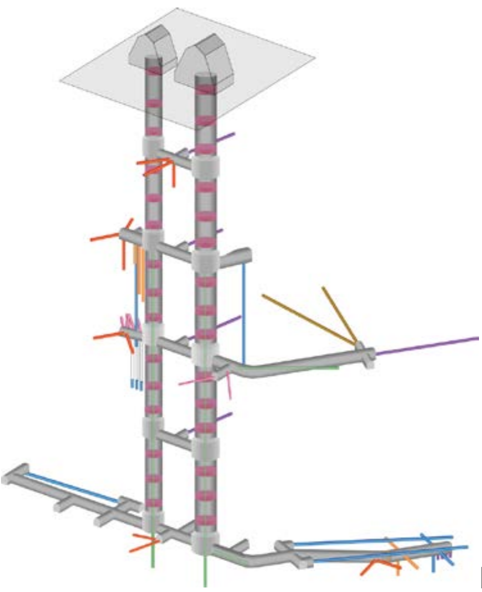
Fig. 2.5 D-hole borehole array and Validation Drift excavation showing location of boreholes and measuring sheets

[4] The second part of this presentation concerned transport times and is therefore presented in section 3.1.2.

Groundwater pressure monitoring around ventilation Shaft at MIU[5]

Ryuji Takeuchi , JAEA, Tono, Japan.

A strong pressure gradient is observed close to the ventilation shaft at MIU (Mizunami Underground Research Laboratory). Head drops from 50 – 100 m above ground level to -300 m within 10 m of the shaft. This strong hydraulic skin effect is due to the shotcrete and excavation process /TAK 10/. The skin effect is also discussed within Coolrep (in Japanese).



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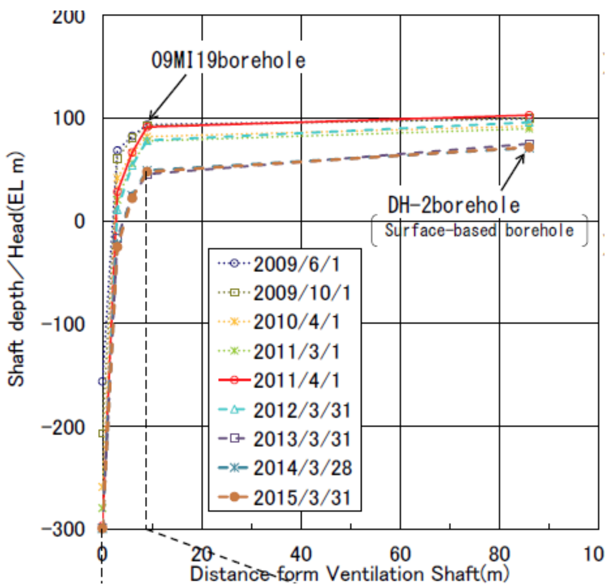

b)

Fig. 2.6 MIU a) Layout of excavations and boreholes; b) Hydraulic head versus distance from shaft

[5] Not presented at the workshop, but material subsequently submitted and included here for completeness.

2.1.3 Repository scale

Skin zone effects – TBD! Some experiences from performing flow and transport experiments in skin zones

Peter Andersson, Geosigma, Sweden

SFR is the repository for low and intermediate waste at Forsmark in Sweden. The observations from SFR concern the almost constantly decreasing inflow to the SFR facility for over 30 years. There are two alternative explanations for this, either an ongoing transient drawdown, or that hydraulic properties in the surrounding bedrock are changing. If changes of the hydraulic properties occur only close to the tunnel wall, a steep hydraulic gradient should be expected to occur, but this is not the case. One explanation could be that these effects arise from a poorly connected fracture network. When we look at safety of a repository, should we then rely on early inflow data and borehole data rather than late inflow data? The answer to this is also dependent on the reversibility of the skin "processes".

A repository will be open or partly saturated for more than 100 years. After closure it is likely that all gas phases will be dissolved, but hydromechanical stress effects may still exists as the rock is replaced with bentonite. Other effects that need to be included are heat effects, microbes, grouting and changes in water chemistry and fracture mineralogy.

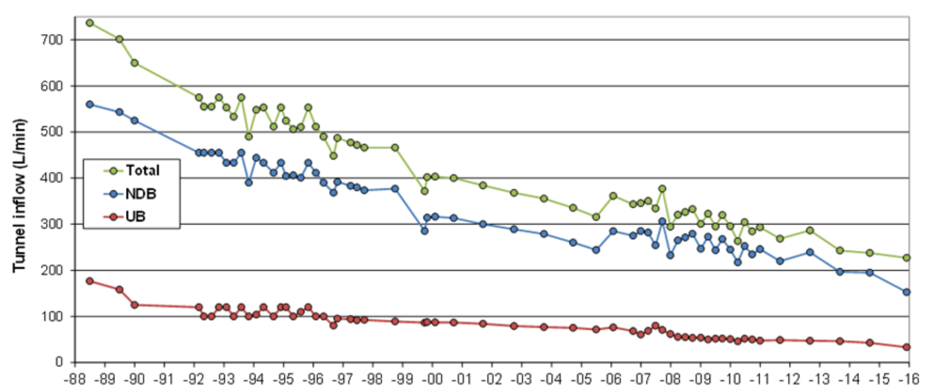

Fig. 2.7 Decline in inflow to the SFR from first operation to 2016. NDB: inflow to access tunnel; and lower construction tunnel, UB: inflow to rock caverns and other tunnels.

2.2 Potential processes and features

Potential permeability reduction processes include:

a) Mechanical processes related to excavation/drilling: stress redistribution and shear, mechanical clogging;

b) Hydraulic and multi-phase flow processes: degassing, desaturation, turbulent flow in channels;

c) Effects of heterogeneity and scaling: channel connectivity;

d) Other flow, chemical, biological or coupled Thermo-Hydro-Mechanical (THM) processes. E. g. fracture closure due to thermal expansion or long-term clogging due to chemical disequilibrium.

2.2.1 Mechanical fracture closure

Excavation is likely to lead to both increased stresses (tangential or hoop stress) and reduced stresses (typically the radial stress). Increasing normal stress typically leads to fracture closure (/RUT 03/, /FRA 10/) with the largest effects at initially low normal stress.

Shear movement can potentially lead to fracture opening (dilation) or closure depending on the fracture normal stress, the fracture surface roughness, the strength of the rock and fracture wall, the magnitude of displacement and the nature of any fracture fill. /PAT 66/ developed a simple model including two modes of shear behaviour in clean fractures:

a) Sliding on inclined surfaces at low normal stress resulting in dilation (e. g. /YEO 98/); and

b) Suppression of dilation and shearing of asperities at higher normal stress.

More elaborate models have been developed (e. g. /OLS 01/) but these two mechanisms typically dominate “clean” fracture shear behaviour although data relating shear deformation to transmissivity change is very limited /FRA 10/.

In fractures containing fill material, the shear behaviour can be significantly influenced by gouge or clay material resulting in lower strength and stiffness and mobilisation of the fill. /JAC 16/ reports significant fracture closure and squeezing out of fracture fill from a shear test on a fracture with breccia infill. Equivalently high-strength fills such as quartz or calcite may increase fracture strength and limit any closure. Additionally, /MAS 17/ points out that artificially produced fractures are better “mated” than natural ones.

The overall geomechanics issues associated with skin/scale effects are summarised in Tab. 2.2.

Tab. 2.2 Geomechanics issues associated with skin/scale effects (from presentation of Japan Atomic Energy Agency/Golder)

issues	**affecting/resulting in**
Stress Distribution	Tectonic (Field Stresses) Underground Openings (Stress Redistribution) Construction Disturbance
Stress Influence on Aperture (Storage, Transmissivity)	Stress concentration/relief – decrease/increase aperture Stress redistribution – channelization? Shear “Critical stress” – increase or decrease aperture
Coupling Mechanics to Hydraulic Pressure	Increase/reduce aperture as pressure increases/drops. Most pressure drop is very near to borehole! Shear – Increase and decrease aperture. Highly dependent on local stress distribution In Situ Effective Stress Updating. Local changes to rock mass stiffness around openings. Stress concentration and stress shadow regions

2.2.2 Degassing

The observations at Stripa /LON 95/ and subsequent work at Äspö /JAR 00/, /JAR 01/ have led to a better understanding of degassing effects around boreholes. The basic mechanism is that gas dissolved in the groundwater at formation pressure out-gases from solution as the pressure drops around an extraction borehole (or potentially the excavation). This gas will preferentially occupy larger pores (channels) in the local fracture network reducing the overall flow. The extent of the degassing zone and the magnitude of flow reduction will depend on the detailed geometry of the flow channels, the hydraulic pressure in the vicinity of the borehole/tunnel, and the gas content. A threshold gas content of 2 – 5 % has been suggested for any significant impact on inflow to tunnels. Measurements of the total gas content and the gas components provide values that lie only slightly outside this suggested range (see Appendix A).

2.2.3 Turbulent flow in channels

Turbulent flow close to the wellbore has been a well-known cause of a skin effect for many decades, especially for gas wells /RAM 64/. The flow regime around an extraction borehole will crucially depend on the detailed geometry of the flow channels. Experimental work on flow regimes within fractures has typically focussed on linear flow geometries but suggests significant non-Darcy effects at Reynolds Numbers ~10 /ZIM 04/. Convergent flow into a borehole may show greater sensitivity to details of the fracture geometry.

2.2.4 Clogging

Clogging of abstraction well screens or the porous rock around a well is a common problem (/VAN 80/, /BRA 83/). /VAN 10/ suggests that the earliest papers on clogging are over 100 years old. Clogging is also commonly observed as a reduction in the efficiency of artificial recharge systems due to physical, biological and chemical processes (/REB 68/, /PER 99/). Clogging can be caused by suspended material, chemical precipitation (e. g. precipitation of iron hydroxides see /HOU 07/, precipitation of carbonate

(/VAN 80/)[6], release of colloids from clay minerals due to change in chemical equilibrium or growth of bio-organisms /VAN 95/.

Although typically observed in porous rocks we might expect clogging processes to act within fractures where flow in channels within the fractures may be restricted by similar processes. This could either be due to fine material created during the excavation or drilling process or to fracture fill material mobilised by excavation-induced deformation.

2.2.5 Scale dependence and connectivity

Strictly this is not a process but a feature of the system and interpretation methods. A skin effect around an excavation has frequently been observed by comparison of measured pressure versus (log) radial distance (e. g. /PUS 03/, /KUL 02/). Distinct slope changes have been interpreted as indicating hydraulic skin. In fracture- or channel-network flow, pressure measurements at any point in the network may be either over- or under-connected to the boundaries (see Appendix C). This connectivity effect will be controlled by the geometry of the network e. g. the length and connectivity of the flow channels. At scales below the typical length scale in poorly connected systems, this may result in poorly defined pressure gradients and a resulting scale effect in the observed pressure vs log distance plot.

2.2.6 Process and feature interactions

The processes listed above may potentially interact, for example turbulent flow may result in greater transport of suspended solids and increased clogging Also the physical processes of degassing, turbulent flow and fracture closure may have different effects according to the geometry of the fracture flow channels (e. g. phase obstruction may act quite differently in a tube of varying aperture compared to a parallel plate fracture).

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[6] Note that precipitation under isothermal conditions requires mixing of waters with different mineralogical composition.

3 Transport skin observations

3.1 Observations

Observations concerning a transport skin have been made in the laboratory as well as in the field. The next subsections therefore comprise firstly observations in the laboratory and subsequently field evidence. Contributions to the skin workshop are again denoted by a bold headline indicating the topic followed by the contributor in plain italics.

The observations presented in the next subsections were made either in the laboratory or in situ or are taken from model calculations. The spatial scales of the observations from these different sources are somewhat overlapping. It is on the order of several centimetres for the laboratory tests as well as for some of the in situ experiments. In situ tests concerning transport phenomena reached a scale of 30 cm. Only the tracer test at Stripa is of significantly greater scale with a transport distance of about 28 m but this appears to be rather a test of the flow than a transport skin (the magnitude of inflow changed significantly – see section 2.1.2).

The granitic material investigated comes from 4 countries but several different types of granite come from Sweden, particularly from Stripa and Äspö. The temporal scales of the tests cover a range from 7 days up to 3.5 years. The considered processes are mainly diffusion and sorption but there are also cases where advection is addressed, in combination with diffusion, with mechanical stresses or with phase change (degassing). Diffusion under different levels of mechanical stress in the rock is investigated also. An initial compilation of the observations concerning a transport skin is given in Tab. 3.1.

Tab. 3.1 Tabular summary of observations

Topic	Material	Location	Spatial scale	Temporal scale	"Skin depth"	Process(es)	Observation	Source
In-diffusion	Äspö granite	Laboratory	Ø36 mm; l=1/2/4 cm	~ 500 days	9 mm Cs,Ba > 18 mm Na	Diffusion; Sorption	Transport skin; porosity distribution	/BYE 98/
In-diffusion	Inada granite	Laboratory	12x12x25 mm	7 days	0.6 - 0.8 mm Cs, Sr, Co	Diffusion; Sorption	Transport skin	/IDE 92/
Stress-dependent diffusion	Various granites	Laboratory	Ø36 mm; l=10 mm	~ 90 days		Diffusion; Mech. stress	Decrease by a factor 2-3	/SKA 85/
In-diffusion	Granite (GTS)	Laboratory	5 mm	130 days	0.4-0.8 mm Na, Ba, Cs, Ni	Diffusion; Sorption	Transport skin	/TAC 15/
Stress-dependent permeability	Granite (Stripa)	Laboratory	Ø60 mm; l=100 mm	-		Advection; Mech. Stress	Decrease by a factor 2-3	/BIR 88/
Stress-dependent diffusivity	Granite (Stripa)	Stripa/ Laboratory	Ø60 mm; l=100 mm	-		Diffusion; Mech. stress	Little difference	/BIR 88/
Rock heterogeneity	Granite	Stripa	250 mm	3, 6, 42 months		Advection; Diffusion	Depth- and direc-tion dependent parameters	/BIR 88/
Tracer test towards VD	Granite	Stripa	~ 28 m	~300 hours	?	Advection	Doubling of break-through time after excavation	/OLS 92/
In-diffusion	Canadian shield	URL	10 cm	2 yrs	~ 5 mm ^{129}I	Diffusion; Sorption	Transport skin	/VIL 03a/, /VIL 03b/
In-diffusion	Granite	Äspö	3 cm	200 days	3 mm Na 5-6 mm Ba 4-8 mm Cs 3-5 mm Co 10 mm Cl 3 mm Ni	Diffusion; Sorption	Transport skin	/NIL 10/, /VIL 05/
In-diffusion	Granite	Grimsel Test Site	30 cm	800 – 1000 days	4 mm Na 3 mm Cs	Diffusion; Sorption	Transport skin	/SOL 13/
Degassing	Granite (Äspö)	Model	5 cm	immediate	4 mm	Advection; Phase change	Transport skin	(Appendix A)
Advection opposing diffusion	Granite (Äspö)	Model	5 cm	~200 days	5 mm ideal Tracer	Advection; Diffusion	Transport skin	(Appendix B)

3.1.1 Observations in the laboratory

In-diffusion of $^{45}Ca^{2+}$, $^{133}Ba^{2+}$ and $^{137}Cs^{+}$ into Äspö diorite and fine-grained granite

Johan Byegård et al., Geosigma, Sweden (from /BYE 98/)

Drill cores with a diameter of 35.1 mm taken from fine-grained granite and from Äspö diorite obtained from the Äspö Hard Rock Laboratory were investigated. Rock discs with a thickness of 1, 2, and 4 cm were placed in a cell for through diffusion experiments. A synthetic groundwater representative for the Äspö 340 m level was used in the tests. Tracers used were $^{45}Ca^{2+}$, $^{133}Ba^{2+}$ and $^{137}Cs^{+}$. Snapshots of tracer profiles in the granitic samples before reaching breakthrough were taken for $^{133}Ba^{2+}$ and $^{137}Cs^{+}$. For both tracers and rock types the tracer profiles are characterized by a steep inclination at the surface followed by a noticeable change of the gradient at a distance of 4 to 6 mm from the surface. The results were found to be similar to those of /IDE 92/, /ITT 90/, and /TSU 93/.

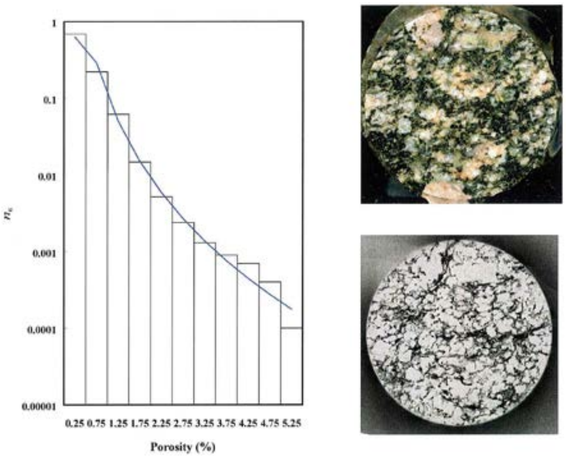

Fig. 3.1 Porosity distribution by PMMA for samples from Äspö diorite

***Measurement of Cs^+ diffusion into Inada granite*[7]**

Kazuya Idemitsu et al., Kyushu University Japan (from /IDE 92/)

In an early investigation of /IDE 92/ the diffusion of *Cs, Sr and Co* in solutions with varying pH-value and temperatures has been studied. The tests ran over 7 days. High resolution measurements revealed a steep concentration gradient within the first millimeter which changes rather abruptly to a lower gradient further on. Reported is a total depth of 3 mm into the rock.

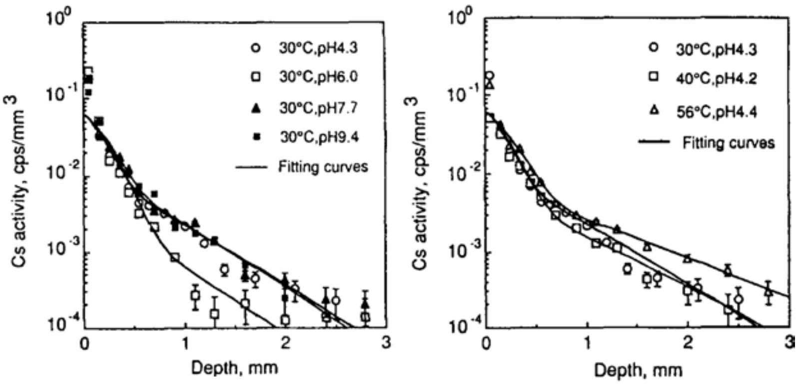

Fig. 3.2 Cesium profiles at varying pH and temperature; from /IDE 92/.

Skin effects around boreholes – Laboratory test

Ivars Neretnieks, Royal Institute of Technology (KTH), Sweden

Laboratory measurements of electrical conductivity and diffusional flux on rock samples clearly showed the effect of increased stress /SKA 85/. The phenomenon was largely reversible although the electrical conductivity showed some hysteresis. The experimental setup and the impact on the through diffusion flux for a biotite gneiss from Svartboberget under increasing stress to 33 MPa are shown in Fig. 3.3 below. The leftmost figure in Fig. 3.3 shows a pressure chamber in which the electrical conductivity in a piece of rock subject to stress is measured. The middle figure shows a piece of rock sandwiched between two filters, one for inlet and one outlet of a diffusing tracer. The right figure shows how tracer flux decreases when stress is applied.

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[7] Not submitted to the workshop but mentioned in the presentation of Yukio Tachi.

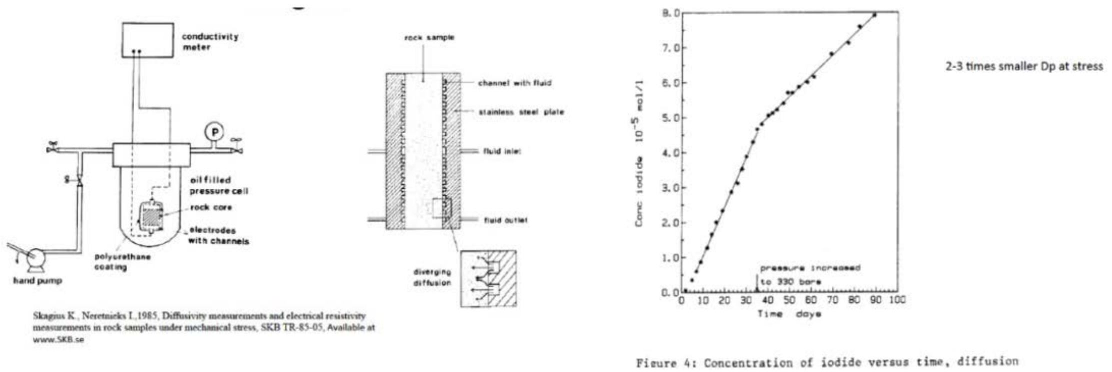

Fig. 3.3 Test setup and concentration of iodide versus time; from /SKA 85/

In another test with granite samples from the Stripa mine the diffusion coefficient under natural conditions was back calculated from diffusion tests and directly measured on samples in the laboratory /BIR 88/. The diffusivities determined in the laboratory were only slightly higher than those obtained in-situ indicating that the diffusion coefficient determined in the laboratory would also be representative for the field despite a totally different stress environment.

The permeability, by contrast, showed a clear dependence on stress. Increasing the stress from 15 MPa to 30 MPa resulted in a decrease of hydraulic conductivity by a factor of three /BIR 88/.

Laboratory observations related to skin effects in Grimsel LTD project

Yukio Tachi, Japan Atomic Energy Agency (JAEA), Japan

Dual profiles of radionuclides in granitic rocks have been observed in both laboratory and in situ diffusion experiments by many researchers. /TAC 15/ focus on laboratory-scale mechanistic understanding of this process and how this can be extrapolated to in situ conditions as part of the Long Term Diffusion (LTD) project at the Grimsel Test Site, Switzerland. Diffusion and sorption of radionuclides ($^{137}Cs^{+}$, $^{22}Na^{+}$, $^{125}I^{-}$ and HTO) in Grimsel granodiorite was studied using through-diffusion and batch sorption experiments. From the depth profiling analysis after the through-diffusion experiments, dual profiles were observed for cations (Cs and Na). Microscopic analyses (EPMA) indicated that the near-surface profiles can be caused by high porosity and sorption capacities in disturbed biotite minerals. The K_d values derived for the disturbed near-surface part were significantly larger than the undisturbed matrix. The K_d values derived from the dual profiles are likely to correspond to K_d dependence on the grain sizes of crushed samples in the batch sorption experiments.

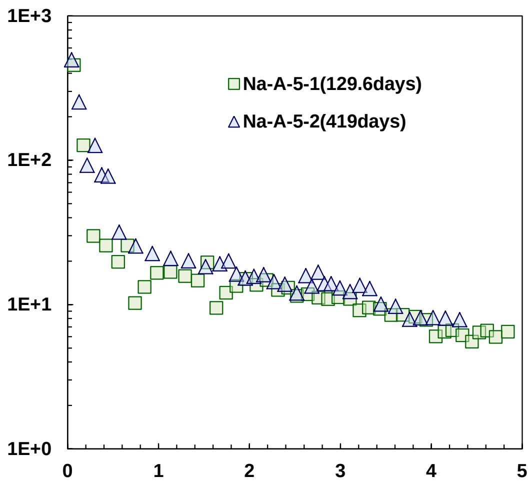

Fig. 3.4 Penetration profiles for Na^+ obtained in the lab at different times.

Based on the above laboratory observations, the near-surface profiles can be evaluated as follows: The high concentrated and sharp-slope profiles are most likely related to the biotite minerals. The sorption for Cs^+ is highest on the most disturbed sawn surface of the rock sample and decreases with the depth corresponding to lower disturbance and porosity. The reason for the difference in slopes of near-surface profiles between Cs^+ and Na^+ can be explained by the difference of sorption mechanisms between Cs^+ and Na^+. The tracer depletion curves and depth profiles for both Cs^+ and Na^+ obtained in the in situ diffusion experiment were reasonably simulated based on laboratory results and their extrapolation to in situ conditions. The fast initial drop in the tracer depletion curve at the start of circulation in the in-situ test can be explained by near-surface sorption and diffusion in the BDZ by taking parameters derived from near-surface profiles of samples used in the laboratory through diffusion tests. The high sorption at the disturbed biotite in laboratory samples is consistent with radiographic observation around borehole for in situ sample and is critically important to evaluate the transport cations in both laboratory and in situ tests.

3.1.2 Observations in the field

***Skin zone effects at Stripa*[8]**

Peter Andersson, Geosigma, Sweden

Transport properties were determined in the SCV experiment (for more information on SCV see section 2.1.2) by performing tracer tests in a fracture zone intersecting the drift before and after excavation.

Tracer travel times to the drift increased by a factor 2 – 3 from transport towards the drill holes to transport towards the Validation Drift which could be explained by the reduction of flow rates due to excavation /OLS 92/. The majority of mass was recovered in the bottom of the drift. Gas bubbles could also be observed in the boreholes at low pressures. A number of different hypotheses were tested of which hydro-mechanical stress effects were considered to be the most prominent effect, with contributions from blast damage effects, gas release (two-phase flow, blasting gases) and chemical precipitations.

***Modelling degassing at a borehole at the HRL Äspö*[9]**

Klaus-Peter Kröhn, GRS, Germany

In the same way that a zone affected by degassing impedes flow due to reducing the effective volume for the liquid (c. p. section 2.1.2) it would also decrease the diffusivity into the rock. This has recently been demonstrated exemplarily by model calculations based on data from the HRL Äspö (see Appendix A).

Anomalous penetration profiles in a Canadian in-situ in-diffusion experiment

Martin Löfgren, Niressa, Sweden

In-situ in-diffusion experiments have been conducted in the Underground Research Laboratory (URL) in at Whiteshell Research Area, Manitoba, Canada. The experiments are reported in /VIL 03a/ and /VIL 03b/.

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[8] The first part of this presentation concerned the flow skin and is presented accordingly in section 2.1.2

[9] Investigation based on ideas from the workshop and presented at the Task Force workshop in Barcelona, October 2017

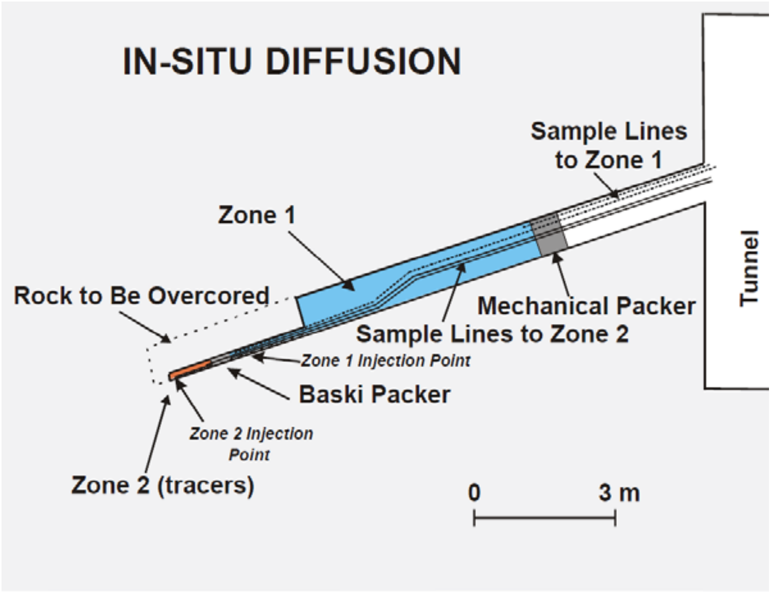

Fig. 3.5 Set-up of the In situ diffusion experiment at the URL in Canada

Penetration profiles of radionuclides were obtained after overcoring. These show a “dog-leg” shape with much lower tracer concentrations in the first slice compared to in the tracer cocktail. The authors suggest a skin effect resulting from stress redistribution as explanation. In their modelling of the tests, the first few millimetres of rock surrounding the borehole were ascribed a very low effective diffusivity to better reproduce the observed shape.

Skin effects around boreholes – In situ and laboratory tests at Stripa

Ivars Neretnieks, Royal Institute of Technology (KTH), Sweden

Three in-situ tests were carried out at the Stripa mine (Sweden) at a depth of 360 m to investigate tracer migration in granitic rock under natural stress conditions i. e. avoiding stress release from taking rock samples /BIR 88/. The influence of circular excavations on natural stresses in the rock decrease rapidly with distance from the axis of the excavation and can be considered negligible at a distance of approximately two diameters from the wall. Hence, the tests were performed in deep vertical boreholes of up to 2 m length to avoid the influence of the drift. The borehole diameter was only 2 cm /BIR 88/.

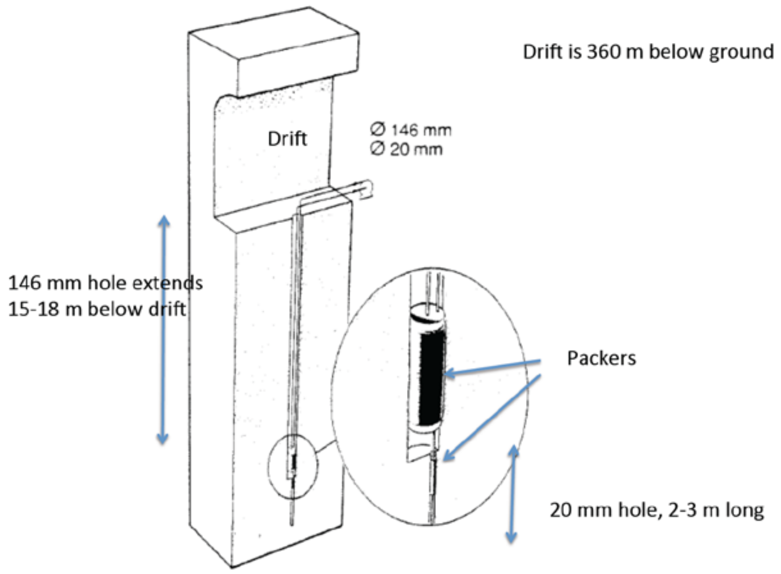

Fig. 3.6 Set-up of the diffusion experiments at the Stripa mine; from /BIR 88/

After terminating the tests and taking samples from overcoring it was found that the horizontal spreading of the tracers was varying strongly with depth. The porosity of the samples was more or less constant. Also the pore size distribution as well as the direction of microfissures did not justify the large differences, leaving only variations in permeability and diffusivity as a possible explanation. A parameter fitting exercise revealed that permeability and diffusivity could vary over an order of magnitude despite a distance between samples in the order of tens of centimeters.

When investigating the migration path with respect to the direction it was found that in some cases there were large differences between the concentrations in different directions. The values for hydraulic conductivity and the diffusion coefficient were thus interpreted as being a function of depth as well as of direction /BIR 88/.

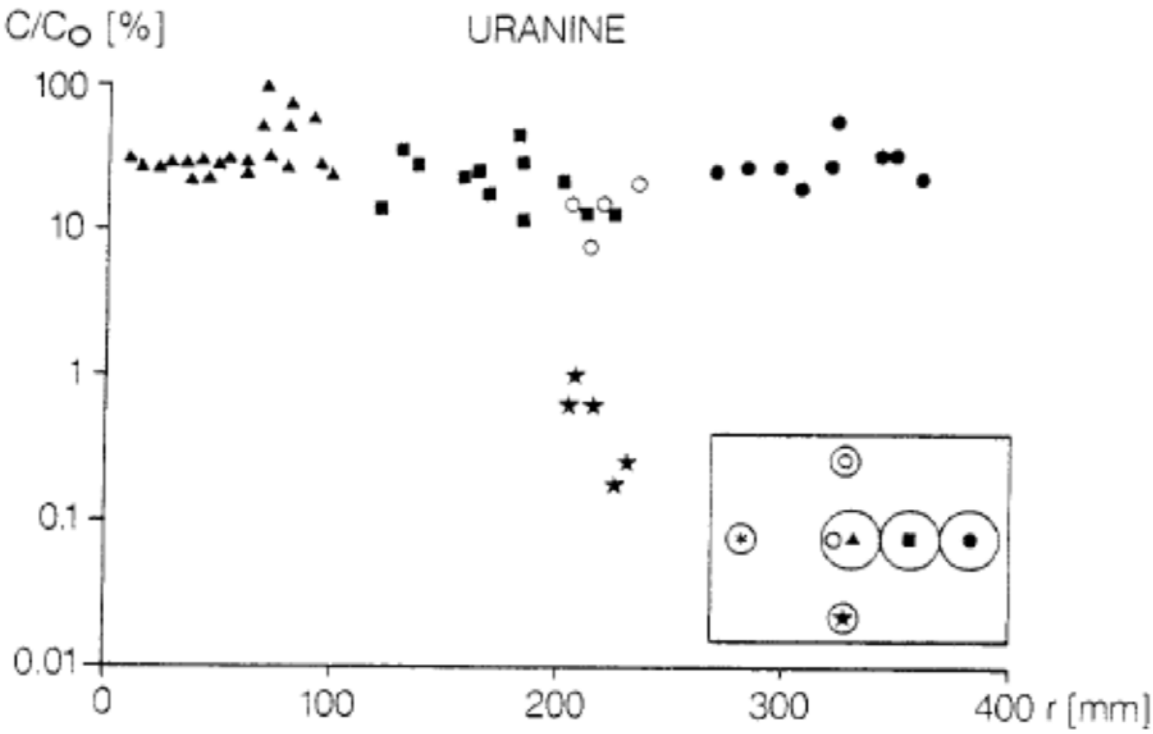

Fig. 3.7 Concentration profiles demonstrating direction dependence; from /BIR 88/

Long Term Sorption Diffusion Experiment (LTDE) at Äspö

Kersti Nilsson et al., Geosigma, Sweden (from /NIL 10/)

The Long Term Sorption Diffusion Experiment (LTDE) is a complex in-situ test that is concerned with diffusion into the granitic rock at Äspö from inside the rock as well as from the surface of a fracture /WID 10/. Multiple tracers were injected into a prepared volume for this purpose. Tracer profiles were afterwards obtained from overcoring and sampling. Penetration depths of at least 2 – 3 cm have been obtained for the non-sorbing or very weakly sorbing tracers (e. g. ^{36}Cl and ^{22}Na, respectively) after 200 days of contact time between the tracer cocktail solution and the rock. The tracer profiles show in general a pronounced version of the profiles with an initially steep and a subsequently a less steep part, the change in slope being found in the range between a few and about 10 mm. These findings were supported by laboratory work by /VIL 05/.

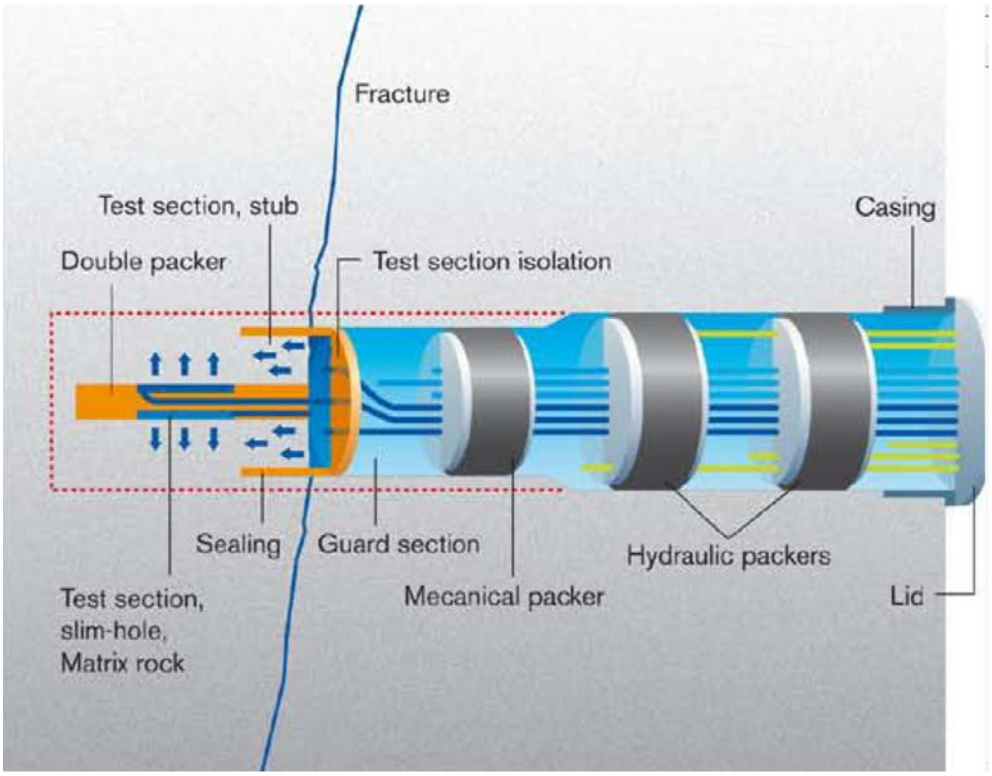

Fig. 3.8 Test set-up of the LTDE-SD experiment at the HRL Äspö

The GTS-LTD monopole-1 in situ diffusion experiment in granite at Grimsel

Josep M. Soler, IDAEA-CSIC, Spain

Several tracers (^{3}H as HTO, $^{22}Na^{+}$, $^{134}Cs^{+}$, $^{131}I^{-}$ with stable I^{-} as carrier) were continuously circulated through a packed-off borehole and the decrease in tracer concentrations in the liquid phase was monitored for a period 789 days from June 2007 to August 2009. Borehole radius was 2.8 cm and the circulation interval was 0.7 m long, between 6.9 m and 7.6 m in depth from the gallery (Fig. 3.9). After the end of the experiment the bore-hole section was overcored and the tracer profiles in the rock analyzed (^{3}H, $^{22}Na^{+}$, $^{134}Cs^{+}$) /SOL 13/.

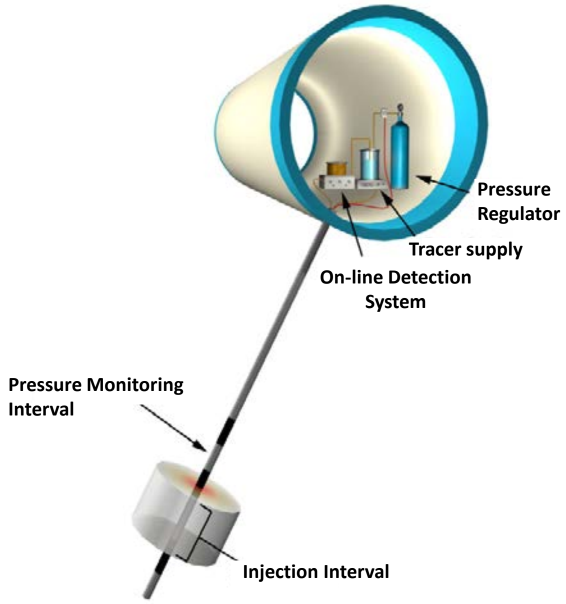

Fig. 3.9 Experimental set-up of the LTD experiment at the Grimsel Test Site

^{3}H and $^{22}Na^{+}$ showed a similar decrease in activity in the circulation system (slightly larger drop for ^{3}H). The drop in activity for $^{134}Cs^{+}$ was much more pronounced. Transport distances in the rock were about 20 cm for ^{3}H, 10 cm for $^{22}Na^{+}$ and 1 cm for $^{134}Cs^{+}$.The dataset (except for $^{131}I^{-}$ because of complete decay at the end of the experiment) was analyzed with different diffusion-sorption models by different teams (NAGRA/IDAEA-CSIC, UJV-Rez, JAEA; Soler et al., 2013, 2015) using different codes, with the goal of obtaining effective diffusion coefficients (D_e) and porosity (ϕ) or rock capacity (α) values.

From the activity measurements in the rock it was observed that it was not possible to recover the full tracer activity in the rock (no activity balance when adding the activities in the rock and in the fluid circulation system).

3.2 Potential processes and features

Processes or effects potentially explaining the skin effect are listed in the following subsections. The sequence does not imply a ranking. Note that these explanations are mostly given in a qualitative manner and still need to be substantiated.

3.2.1 Porosity distribution

Porosity distributions have been measured for different Äspö granites /BYE 98/. Subsequent modelling of diffusion and sorption of a diffusion experiment in these rocks with a domain that was segmented by volume according to different porosity classes showed a considerably better agreement with measured tracer distribution data than a homogeneous model /JOH 99/. After dividing the model domain and assigning different porosity values to each subdomain, fitting was possible with just two global fitting parameters, namely the diffusion coefficient and the K_d-value.

3.2.2 Inhomogeneity of the rock

Strongly varying values with depth and direction for hydraulic conductivity as well as for the diffusion coefficient have been found in the granitic rock at the Stripa mine at typical distances of a few decimeters /BIR 88/. This can be generally interpreted as a consequence of inhomogeneity of the rock.

It can further be speculated that the inhomogeneities are due to micro-fractures. It is a common assumption that fractures exist on all length-scales. In /DER 03/ for instance it is claimed that “The connected porosity in crystalline rock is mainly made up of micro fractures …”.

3.2.3 Degassing

Modelling degassing at a hypothetical borehole at the HRL Äspö has been performed in two steps. First, flow and pressure distribution at the borehole have been calculated assuming the borehole was surrounded by intact rock. Based on the flow data as well as on gas content data it was then estimated if and when the dissolved gases would evolve. The resulting thickness of the zone affected by degassing was estimated to be in the range of a few millimetres (Appendix A). However evolution of such a zone requires free outflow conditions.

3.2.4 Advection opposing diffusion

Based on the same flow model as the one about degassing (section 3.2.3), a transport model simulating diffusion into the rock was run. In this setup, the direction of tracer transport (into the rock) is opposing the direction of the groundwater flow (out of the rock). The resulting radial tracer profiles were compared with profiles that were calculated without advection (Appendix B). While advection can increase the tracer concentration gradient in a in-diffusion experiment close to the opening under realistic flow conditions, the calculated profile lack the distinct sharp edge that has been found in other measurements (see Fig. 3.2 or Fig. 3.4).

3.2.5 Borehole disturbed zone

A Borehole Disturbed Zone (BDZ) was assumed to fit the experimental observations at the Grimsel test site /SOL 13/. The extension of the BDZ (1-2 mm) was estimated from the experimental data showing an increased sorption of $^{22}Na^{+}$ and $^{134}Cs^{+}$. This size coincides with the mean grain size of the quartz and feldspar grains which would be consistent with a more accessible surface area in the BDZ.

3.2.6 Rock desaturation

Under operating conditions a tunnel or borehole surface is subject to ventilation which carries evaporating water to a certain extent away from this surface. In the hydraulically rather tight rocks that are envisaged for radioactive waste storage the permeability is too low to replenish this loss of water. This leads to an unsaturated zone at the rock surface whose thickness depends on the permeability. From the ventilation test at the GTS a desaturated zone thickness (defined by a gas saturation in excess of 10 %) in the range of 0.5 metre has been estimated by means of modelling /FIN 95/.

3.2.7 Mechanical stress redistribution after excavation/drilling

A circular hole in a homogeneous medium which is subject to mechanical stresses, causes stress redistribution in such a way that stress components normal to the surface are zero while the tangential component increases. In a homogeneous elastic medium, with isotropic far-field stresses, the tangential stress at the tunnel boundary is twice the far-field stress. Mechanical fracture closure as discussed in section 2.2.1 leads to a reduction of the aperture and thus a decreased permeability/transmissivity which decreases not only flow but also the transport capacity in terms of advection and diffusion.

3.2.8 Excavation induced structural changes

Already in the framework of the Site Characterization and Validation project at Stripa a thorough discussion of possible excavation-caused structural changes was presented as potential explanations for the observed skin effect /OLS 92/. The following subsections are taken from this source together with one contribution from the workshop.

Shear displacements due to excavation
from /OLS 92/

“The excavation of the drift will cause displacements towards the drift. Fracture opening and closure is mostly related to change in normal stress … . Shear displacements along the fracture planes could cause either increases or decreases in permeability. If normal stresses are high, …, shear displacements are expected to cause decreased permeability due to lack of dilation. The magnitude of such reductions could be half an order of to one order of magnitude (Makurat et al., 1990, Gale et al., 1990b)[10]. Hence, permeability reductions due to shear displacements does seem a potential process which could contribute to the observed reduction in inflow when planar mineralized joints are present.”

“The blasting will also generate compressional and shear waves which will propagate through the rock. The waves are accompanied by rapid displacements and increases in stress levels (dynamic loading) which could change fracture transmissivity. The magnitude of dynamic stress load can be estimated from estimates of particle velocities due to blasting. At distances from the blast hole larger than 1 m, particle velocities due to blasting are expected to be less than 1 m/s (Holmberg and Persson, 1980, Ouchterlony et al., 1991)[11]. A particle velocity of 1 m/s corresponds to a stress load on the order of 10 MPa.

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[10] /MAK 90/, /GAL 90/

[11] /HOL 80/, /OUC 91/

As particle velocities are inversely proportional to distance from the blast hole significant dynamic loading effects are only expected to occur near the drift wall. However, dynamic loading could also affect fractures nearly perpendicular to the drift which are virtually unaffected by the stress redistribution around the drift."

Effects from blasting – creation of fractures

from /OLS 92/

„The act of blasting will damage the rock by creating new fractures … . The new fractures … will preferentially be radial fractures from the blast hole (Christiansson and Hamberger, 1991, Martin and Kozak, 1992)[12]. Such fractures could increase axial conductivity along the drift and provide connections between the drift and hydraulically connected fractures adjacent to the drift. … Blast induced fractures are expected to cause increased inflow to the drift as they open new flow paths, but the increase is expected to be moderate as these fractures are subject to the highest tangential stresses around the drift opening."

Effects from blasting – gases from explosives

from /OLS 92/

"The gases generated during blasting … will be forced into the fractures and will reduce permeability as the gas fills the voids. … After excavation the gases will be flushed out of the rock with the groundwater flowing to the drift. The presence of blast gases is expected to cause a temporary reduction in permeability but as the gases are flushed out permeability is expected to return to normal. The return to steady state is normally expected to take anything from a few days to a couple of weeks if the water was not saturated with these gases (Neretnieks, personal communication)."

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[12] /CHR 91/, /MRT 92/

Effects from blasting – flow path obstruction by granitic fine particles
from /OLS 92/

"It is also conceivable and even probable that the blasting may shake loose some of the fine grained particles which will be transported by the water and deposited in narrower flow paths. This is a possible mechanism active on fractures of all orientations which may reduce the inflow around a drift."

Effects from blasting – flow path obstruction by drilling debris
from /OLS 92/

"Drilling debris was produced during the drilling of the blast holes. This debris could have been transported into fractures blocking the narrower flow paths and resulting in a reduced permeability near the drift. More drilling debris is produced during percussion drilling of blast holes than during drilling of cored holes. This effect is compatible with the larger flow reduction in the drift compared to the boreholes (in the Site Characterization and Validation Experiment (SCV))"

The skin effect – an established fact in wells in sedimentary rock
Martin Löfgren, Niressa, Sweden

This contribution has already been discussed with a view to a flow skin in section 2.1.1. The ideas of fines from the drilling fluid clogging pores as well as that of swelling clay particles, however, also suggest an influence on tracer migration from the borehole into rock.

3.2.9 Clogging

Clogging the pore space of the rock and possibly also the open spaces of fractures can not only account for a flow skin but also for a transport skin. Various mechanisms for clogging are discussed in subsection 2.2.4.

3.2.10 Post-test artefacts

Artefacts caused by the preparation and handling of samples, particularly if coming from an in-situ test are also to be considered. One possible mechanism is given next as an example of such processes.

Can capillary effect have caused the low concentration tail in the cores?

Ivars Neretnieks, Royal Institute of Technology (KTH), Sweden

The observed drawn out profiles could be caused by capillary generated transport during the time when the large cylinder over-cored from the experimental site was exposed to air with relative humidity less than 100 %. The perimeter of the 28 cm diameter core diameter when exposed to the air dries and capillary forces develop sucking water very unevenly from the slim hole in the centre of the core in which the tracer cocktail had been circulated. Capillary transport can be very fast and unevenly distributed. The finest pores suck the water out to the surface. The water meniscus in the larger pores recedes. A small amount of the tracer could be carried from the slim hole radially to the surface of the cylinder. The process is illustrated by inverted paper chromatography. The figure below shows how an ink spot on a water soaked filter paper rapidly migrates toward the right end where the paper between two glass sheets is dried.

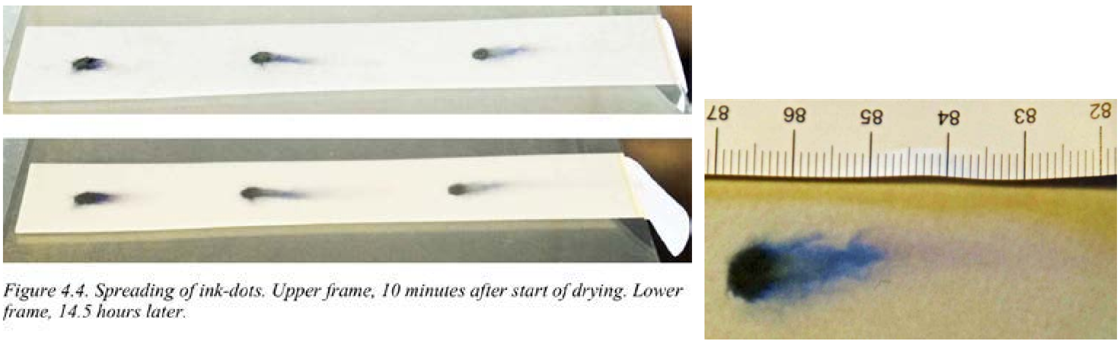

Fig. 3.10 Spreading of ink dots on water soaked filter paper; top left picture: 10 minutes after start of drying; bottom left picture: 14.5 hours after start of drying; right picture: close-up

3.3 ”Skin-effect” depths

A final observation concerns the tracers involved and the affected “skin-effect” depths. Because of the delicacy of the transport process the evolution of the tracer profiles with time cannot be observed. Only the profiles at the end of a test are known. Of particular interest is thus the relation of skin depth to test duration which is of course tracer-dependent because of different sorption properties. The plot of depths over temporal scales in Fig. 3.11 indicates a rather loose relation.

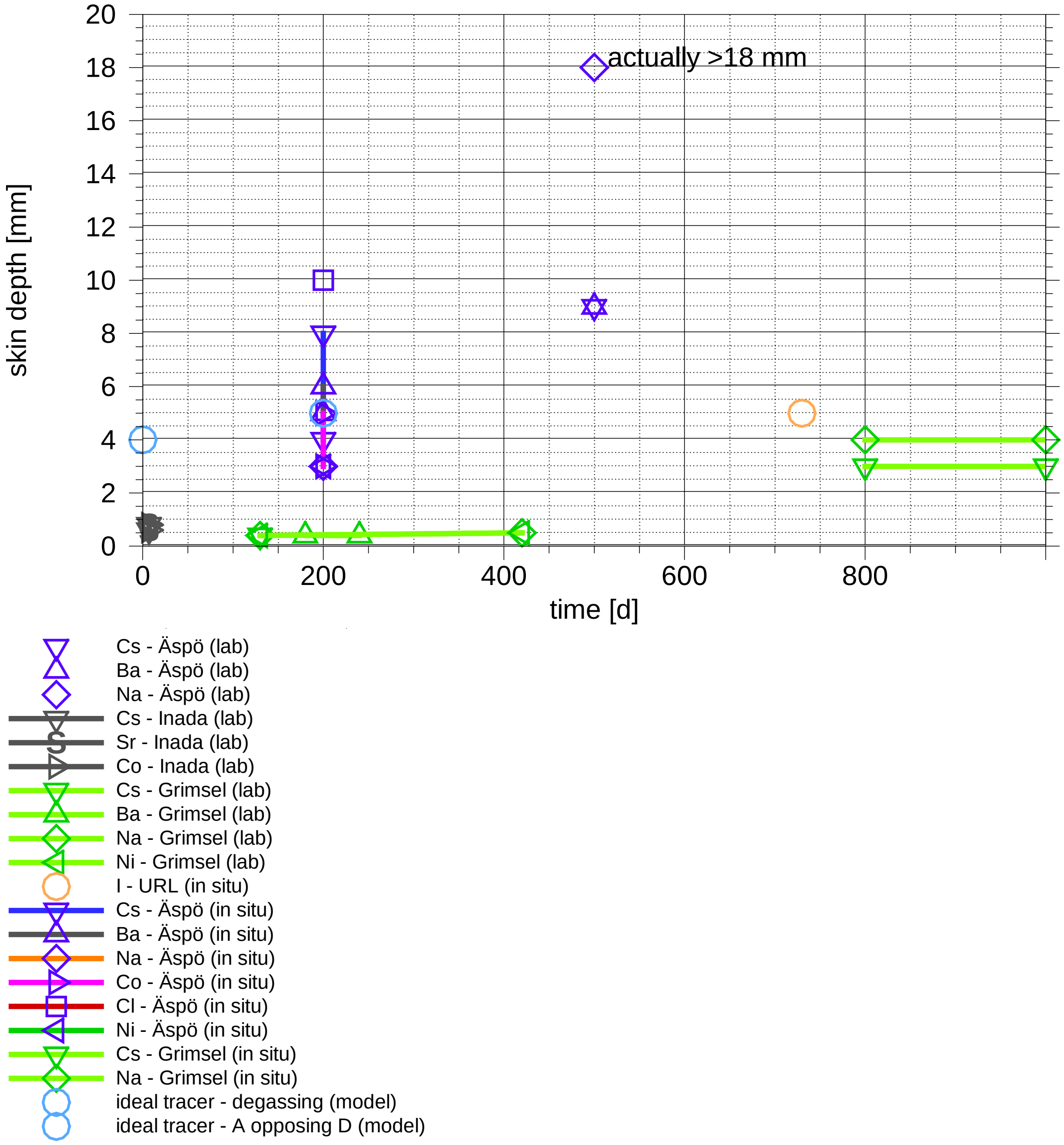

Fig. 3.11 Skin depth as a function of testing time, tracer and location

4 Conclusions and recommendations

4.1 Summary

The observations of skin effects for flow and transport in crystalline rock are typically different in nature. Skin effects in flow dominantly relate to changes (reduction[13]) in fracture flow due to the creation and presence of the opening. Skin effects in transport dominantly relate to small-scale (mm-10s mm) variability in rock matrix properties.

These differences relate both to processes and investigation methods. Transport observations largely coming from tests on core while flow observations relating to borehole or tunnel scale investigations. The only larger scale transport observation is that associated with the Stripa SCV (SDE and Validation Drift) experiments and can probably be ascribed to the changes in the flow field.

4.1.1 Flow

Skin effects have been observed around boreholes and tunnels. These observations derive from underground research laboratories where hydraulic properties are reasonably understood, boundary conditions can be controlled, and detailed testing methodologies applied. It is possible that such effects are much more widespread but difficult to identify under less well-controlled situations[14].

A range of causes for skin effects have previously been considered, although it has not always been possible to conclusively identify the relevant processes in each case. The processes considered were:

- Two-phase flow and degassing;
- Turbulent flow in fractures/channels;
- Fracture/flow channel closure due to normal and shear deformation;
- Fracture/flow channel heterogeneity and scale effects;

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[13] Increase in flow is usually ascribed to Excavation Damage Zone effects – often in the axial direction along the tunnel.

[14] A key requirement is the ability to determine the “undisturbed” flow properties relative to which the influence of the skin effect occurs.

– Physical or chemical clogging of flow-channels.

The complexity of fracture flow is such that it may be difficult to identify the relative contributions of these different processes.

The work on degassing at Äspö shows that knowledge of groundwater gas content is an important indicator of such effects. Similarly understanding of two-phase flow in fractured rock has increased following the work at YMP and GTS.

For the geomechanical aspects a large amount of experimental work has been performed over the last 10 – 15 years to understand fracture deformation and its effect on permeability. These experiments demonstrate the processes associated with shear movement on fractures and the potential for significant permeability increase. However, although the mechanisms are understood the ability to predict the effects is limited by the knowledge of the details of the fracture systems.

The effects of mineral dissolution/precipitation, microbes or fines reducing flow, and chemical effects also require further study.

4.1.2 Transport

Experiments on core and single boreholes at Stripa, Äspö and AECL URL show consistent patterns of small-scale variability due to excavation/stress-induced property changes together with the influence of inherent heterogeneity potentially due to small scale (micro) fracturing.

There is clear evidence for greater sorption near the rock surface. This arises from disturbance of mineral grains by the excavation process (even with purely mechanical methods such as core-drilling or TBM). At a minimum the surface is typically disturbed to a depth of the grain size, resulting in increased porosity and micro-cracking and increased surface area of reactive minerals.

Other processes, e. g. stress-dependent permeability and porosity, degassing and counter advection, may all further affect diffusion close to an excavation.

4.1.3 Relevance to repository performance

Some of the processes considered are only relevant to the site characterisation and operational periods of a geological repository and it is largely the irreversible mechanical processes that are expected to have a continued influence on the repository long-term safety.

4.1.4 Tabular summary of processes

A concise tabular summary of the various processes related to skin effects is given in Tab. 4.1 which is based on the more detailed process characteristics compiled in Appendix D.

Tab. 4.1 Tabular summary of processes

Effect	Cause	Process → affecting	Reversibility	Timescale	Spatial scale	Repository relevance: Operational phase	Repository relevance: Post closure phase	Key parameters
Groundwater degassing	Hydraulic pressure reduction below bubble point	(H) → f,t	Yes	Instantaneous begin + slow dynamics	Likely very close to outflow	Potentially	No	Groundwater gas content, two-phase flow parameters and fracture flow geometry
Turbulent flow	High flow velocity pump test	(H) → f	Yes	Instantaneous	Depends on fracture flow geometry	Yes	No	Fracture flow geometry
Capillary and evaporation barriers	Drying and capillary forces	(H) → f	Yes	Slow	Around the excavation	Yes	(only at sites such as Yucca Mountain)	two-phase flow parameters
Fracture normal closure	Stress redistribution due to excavation	(M) → f,t	Depends[15]	Near instantaneous	close to excavation boundary	Yes	Potentially	In situ stress, fracture stiffness and filling
Shear deformation	Stress redistribution due to excavation	(M) → f,t	No	Near instantaneous	Likely close to excavation boundary	Yes	Yes	In situ stress, fracture shear strength and fracture filling
Grain scale disturbance at excavation surface/ Borehole disturbed zone	Drilling	(S) → t	No	At excavation	Typically scale of mineral grains – can be greater in high stress environments	No	Minimal	Excavation method and distribution of reactive mineral surfaces

[15] Likely to be reversible for small stress changes but may be irreversible where either the fracture is completely unloaded or where fracture closure results in damage to asperities or deformation of fracture fill.

Effect	Cause	Process →	Reversibility	Timescale	Spatial scale	Repository relevance		Key parameters
Scale/ connectivity effect	Structural	(S) → f,t	No	Near instantaneous	Depends on the scale and connectivity of the flowing features	Yes	Potentially	Fracture flow geometry
Inhomogeneity of the rock[16]	Structural	(S) → f,t	No	Instantaneous	dm-scale	Yes	Yes	Bandwidth of permeability and diffusion coeff.
Clogging by precipitation	Geochemical imbalance in produced fluids	(C) → f	No	Slow	large scale	unclear	Yes	mineralogical groundwater composition
Clogging by fines	Drilling, Release of clay flakes	(M) → f,t	No (?)	Quick	Pore-scale	No	No	Pore & particle sizes
Pore size distribution	Structural	(S) → t	No	Instantaneous	mm- to cm-scale	No	Yes	Pore size distribution; Flow channel geometry
Advection opposing diffusion	Flow and solute transport	(H) → t	Yes	Instantaneous	Depends on flow rate	No	No	Permeability, Storage coefficient
Rock desaturation	Ventilation, drainage, blasting	(H) → f	Yes	Days/weeks?	Metre-scale	Yes	No	Two-phase flow parameters
Post-test artefacts	Various	(?) → t	N/A	Dependent on nature of artefact	Dependent on nature of artefact	Depends	Depends	Dependent on nature of artefact

(H) - hydraulic process; (M) -mechanical process; (C) - chemical process; (S) - Spatial structure of hydraulic properties.

f - flow; t - transport

[16] Possibly related to “scale/connectivity effect”

4.2 Conclusions

Skin effects may be significantly under-reported due to the difficulty of characterising such processes in fractured rocks. It does not help that the expression “skin” is commonly used as a placeholder for any impediment of flow or transport, potentially relieving the user of the necessity to explain its nature. The range of possible processes together with difficulties in characterisation have led to a variety of observations and proposed explanations concerning the skin effect.

We have structured this report by observations, dividing the contents according to the affected repository-relevant processes, namely groundwater flow and solute transport. The decision appeared to be natural as the spatial scale of the related observations is quite different. While a flow skin, as a general rule, appears to be associated with scales on the order of a metre, the observed transport skins have a thickness on the mm- to cm-scale. This is in part related to the different experimental methods used in the two types of investigation but may also reflect differences in the processes involved and the time-scales over which they are observed.

Tracer transport tests require much more finesse to obtain a reasonable resolution of the results than flow measurements. The sensitivity of the tracer detection process also suggests that the sample conditions after termination of the experiment must be taken into account. Great care must therefore be taken at identifying all relevant processes that might have affected the interpretation of the tracer concentration data.

From the observations presented here we believe that no single cause explains all the observations and that in some cases it is possible that multiple processes and features of the flow system interact to cause observed skin effects

Unfortunately, the proposed explanations for skin can in many cases not be quantified for a specific situation. Often crucial information is missing, even in well-controlled environments. In part this relates to the heterogeneity of the rock and diversity of possible processes.

For example while shear deformation can potentially cause permeability reduction, strong variability in hydraulic (channels) and mechanical properties (stress, strength and fracture filling) typically prevent conclusive associations between deformation and changes in flow behaviour.

Discussing the relevance of pore clogging by fines from borehole drilling requires detailed knowledge about particle sizes and flow channel geometry on the pore scale. Both are presently rarely known. This is unfortunate as effects like clogging by fines or degassing have the potential of explaining both flow and transport skins.

For these reasons typically only qualitative descriptions of these effects can be given at the moment and predictive models are absent entirely.

Two-phase flow and degassing effects including desaturation of the rock due to ventilation can be readily identified. If necessary, the potential impact of these processes can be anticipated and characterised (e. g. /GHE 04/). Mechanical fracture and flow channel closure are to be expected locally around excavations but will only have a significant hydraulic effect where favoured by the stress conditions, fracture surface properties and flow system geometry.

Small-scale variability in rock matrix properties close to excavations is also to be expected due to the inevitable disturbance of the mineral grains and porosity (microfractures) due to the excavation process. The extent of the effects will be dependent on the magnitude of excavation-induced disturbance and the accessibility of reactive mineral surfaces.

Variability of hydraulic properties exists apparently also in the undisturbed state of the rock. Significant changes of permeability and diffusivity on a decimeter-scale have been observed in the rock at Stripa and thus may be found also elsewhere. For Äspö diorite and fine-grained granite a distinct porosity distribution has been found raising the question about an impact of tracer migration velocity on the pore-scale.

Another wide field of possible reasons for a skin can generally be described simply by clogging of the flow channels. This can be caused by

- excavation (e. g. dust from blasting, particles from drilling fluids),

- chemical precipitation (either by mixing of waters of different mineral composition or under non-isothermal conditions due to the temperature-dependent solubility limits), or
- release of colloids from clay minerals due to change in chemical equilibrium or growth of bio-organisms.

Further effects that might add to a skin not in general but in a particular case, artifacts from post-test sample treatment or unexpected specific flow conditions should also be mentioned here.

4.2.1 Relevance to site characterisation

Skin-effects resulting from artefacts of testing methods (e. g. fracture closure/degassing due to large hydraulic drawdowns, or grain-scale damage associated with excavation) can influence the derived formation properties potentially resulting in a non-conservative bias in estimates of formation properties. Such biases can be minimized by awareness of the potential processes and appropriate test design. However, skin-effects due to the flow geometry (channeling) may be unavoidable and need to be addressed by the use of appropriate conceptual models and analysis methods.

4.2.2 Relevance to performance assessment

Permeability reduction around repository excavation or channeling of flow away from such excavations is likely to be beneficial to overall repository performance but uncertainty in the relevant processes and the timescales over which they may act makes it difficult to take credit for such performance. However, these effects still need to be considered within the context of the repository evolution (e. g. resaturation).

4.3 Recommendations

There are two good reasons to commence a systematic investigation of the true nature of skin effects. First, not having a good grasp on the physics of flow and/or solute transport processes in the rock close to borehole or tunnel walls undermines the confidence in predictions of the evolution of a repository. The second one is equally important and concerns the interpretation of in-situ tests. Data and conclusions from such tests can be biased by an incomplete understanding of the processes involved, which is problematic since they form the basis of predictive models.

In some cases it is possible that plausibility checks based on different conditions might help to eliminate inapplicable explanations. Where processes are complex and data is at least partly available, numerical modelling could be performed and sensitivity analyses used to check if the process in question is capable of causing a skin effect. If there is a potential at all, the related range of parameters can be identified deciding more conclusively about the viability of the related explanation. Moreover, it is expected that there are still documented observations of the skin effect that are not included in this compilation. Further investigations of the skin effect should therefore be accompanied by a literature survey aiming at identifying additional helpful references.

In many cases it will be necessary to provide data on key features first before investigating the relevance of an effect in more detail. This comprises a wide range of different measurements with quite different degrees of complexity. It may start with basic data such as particle sizes and end up with testing the interplay of mechanical loading of fractures with a natural roughness and the related hydraulic response. In any case there will be subsequent analyses by numerical models again.

With a view to the surprisingly little variation of skin depth with the strongly varying time frames of the tracer tests it might prove enlightening to examine the tracer migration dynamics in more detail.

Recommendations for future field studies are:

- Two-phase flow and degassing: evaluate the potential for unsaturated conditions (groundwater table, tunnel inflows, humidity and ventilation conditions) and degassing (groundwater gas content).

- Chemical precipitation or particulate clogging: characterise groundwater chemistry (and expected evolution) and suspended solids. Groundwater chemistry evolution will be particularly important for long-term flows.

- Mechanical effects of excavation on flow: While it is possible to evaluate the potential for fracture opening or closure and to minimise EDZ development by choice of excavation geometry and method, it is likely that quantitative prediction of the mechanical effects of excavation on flow will remain impractical. The effects of shear deformation on channel flow and permeability reduction due to fracture surface damage and mobilisation of fracture filing material requires further experimental study.

- Mechanical effects of excavation on transport: grain-scale disturbance of the rock is clearly capable of altering porosity and sorption properties. Small-scale post-excavation characterisation can identify this disturbance.

- Hydraulic testing campaigns such as those described by Morosini (see section 2.1.1) provide useful information on testing artefacts and the importance of non-Darcy flow processes such as turbulent flow and coupled hydromechanical effects. Comparison of injection and withdrawal behaviour is a useful technique for estimating the potential magnitude of near-wellbore effects.

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Table of figures

List of tables

Appendix A Tentative model for degassing at a borehole at Äspö

It has often been proposed that a possible explanation for a flow or transport impeding skin zone around a geotechnical opening could be the evolution of dissolved gas under a pressure decrease. This approach was followed from a theoretical point of view by quantifying this effect for a situation that is representative for the LTDE at the HRL Äspö (Task 9 of the GWFTS Task Force). It is based on gas content data from water samples retrieved from Äspö as well as a flow model reproducing the flow conditions at a borehole. Two specific cases were closer looked at: the immediate pressure decrease due to drilling and the subsequent flux of dissolved gas with the groundwater under the decreasing pressure towards the borehole.

The gas content has been analyzed at least by two different groups at different times /KUL 02/, /NLA 16/. While the two data sources disagree on the total gas content by a factor between 3 and 4 (18 compared to 69 $ml_{gas}/kg_{formation\ water}$), they consistently show that nitrogen is by far the main constituent. Gas concentrations were converted into partial pressures according to Henry's law and compared with the hydraulic pressures from the model. This comparison indicates that

– degassing does not necessarily happen since gas evolution occurs only in the water with the high gas concentration, that
– the local gas concentration immediately after drilling should be less than 4 %, and that
– the thickness of the desaturated zone is in the order of millimetres.

Based on certain assumptions concerning gas evolution and flow the increase rate of the resulting gas saturation in the unsaturated zone was determined to be in the order of 10 to 14 %/d which can be regarded as quite slow. Further considerations lead to the conclusion that gas flow from the matrix is rather intermittent than continuous. The zone immediately affected by degassing after drilling is not expected to grow with time.[17]

[17] Presented at the workshop of the GWFTS Task Force in Barcelona, October 2017.

Appendix B Advection opposing diffusion

The spreading of a pressure wave in a groundwater system can basically be described by Fick's second law where the diffusion coefficient is defined as the ratio of hydraulic conductivity and specific storativity. Very few and basic properties of matrix and groundwater are required for that purpose.

Using data that is consistent with the situation at Äspö allows doing scoping calculations concerning the de-pressurization of the groundwater flow system around the LTDE. The effect of excavating a circular tunnel with a diameter of 5 m as well as a borehole of 36 mm in a vertical cross-section of 400 m by 400 m was simulated.

The results indicate that the pressure field at Äspö would be far from steady-state conditions as a pressure decrease cannot be found beyond a distance of 200 m from the openings. Also an almost not varying outflow can be observed in the model.

Adding a simulation of the diffusion test shows furthermore that for the given choice of parameters there is a clear influence of the flow field on the radial tracer profile. Increasing speculatively the testing time of the LTDE to 400 days reveals that the calculated tracer profile is possibly already at steady-state after the actual 198 days (see Fig. B.1).

It has to be kept in mind, though, that these results are rather of orientating character as the influence of background fractures on the overall matrix permeability and storativity has not been considered in the model. More realistic results are furthermore expected from a full 3D-model acknowledging the whole field of boreholes and tunnels as well as the sequence of excavations and drillings.[18]

[18] Presented at the workshop of the Task Force on Groundwater Flow and Transport of Solutes in Täby, May 2017.

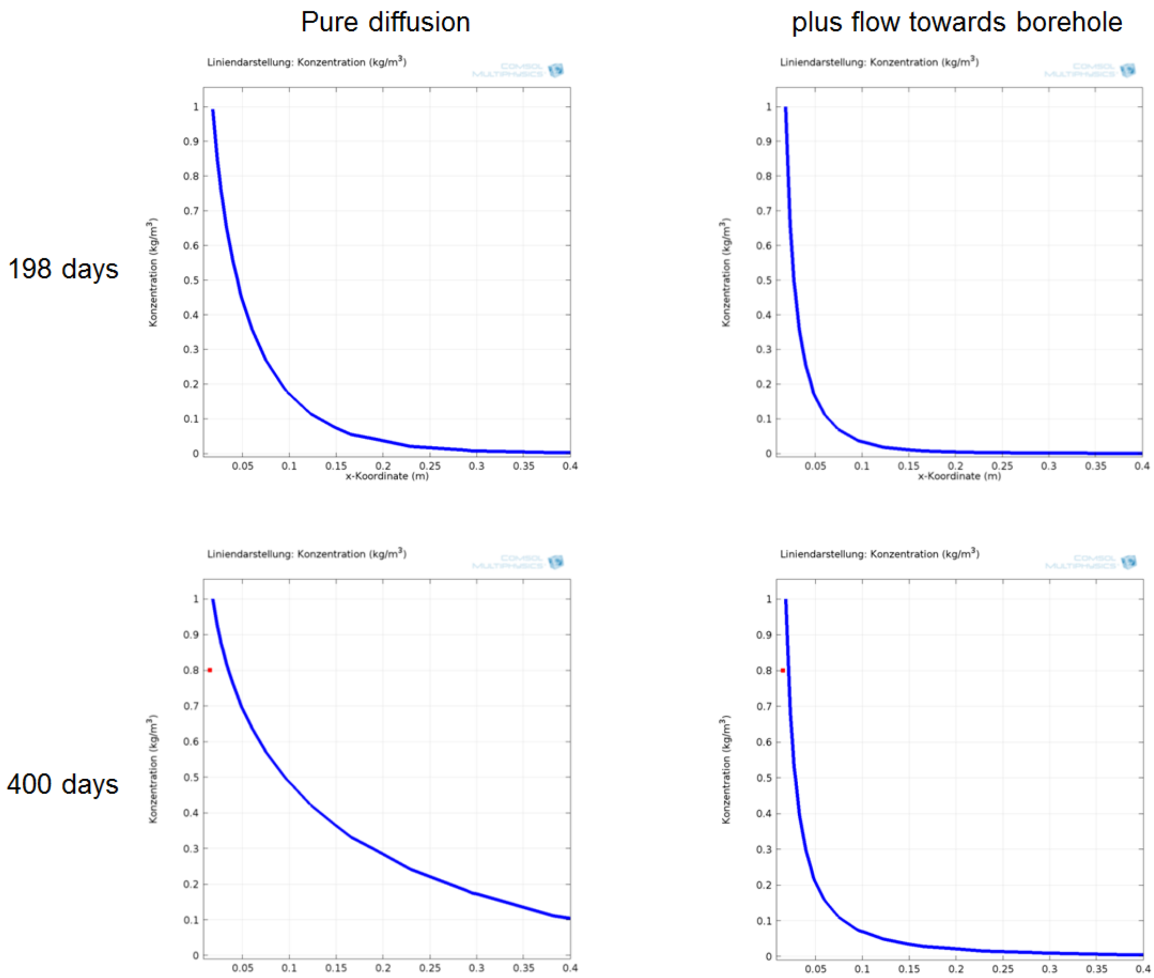

Fig. B.1 Computed radial concentration profiles for two cases at two different times;
left column: results for pure diffusion at 198 and 400 days,
right column: results for diffusion and concurrent outflow.

Appendix C Simple model of fracture connectivity and skin

The purpose of this simple model is to illustrate how profiles of hydraulic head versus radial distance from an excavation may be influenced by the connectivity of a fracture system.

The model is based on the Thiem equation for steady radial flow in an annulus.

$$T = \frac{Q}{2\pi(h_2 - h_1)} \ln\left(\frac{r_2}{r_1}\right) \tag{C.1}$$

Or equivalently

$$h_2 - h_1 = \frac{Q}{2\pi T} \ln\left(\frac{r_2}{r_1}\right) \tag{C.2}$$

- T - transmissivity [m^2/s]
- Q - flow [m^3/s]
- r_1 - inner radius (excavation) [m]
- r_2 - outer radius – constant head boundary [m]
- h_1 - hydraulic head at inner radius r_1 [m]
- h_2 - hydraulic head at outer radius r_2 [m]

We assume that hydraulic head in the fracture network around a circular excavation will on average follow the Thiem equation, but that parts of the fracture network are either over-connected (show head equivalent to a smaller radius) or under-connected (show head equivalent to a larger radius) to the inner excavation boundary. Fig. C.1 shows the dimensionless head for the Thiem equation and for cases where the head measured is over-connected (red) or under-connected (blue) by 10 % and 20 % of the radial distance to the constant head outer boundary. The average of the over and under connected curves is shown as gray dashed lines and shows a clear trend that might be interpreted as a skin effect.
There is a further potential for bias in that intervals with atmospheric pressure (i. e. that directly connect to the excavation) may be ignored.

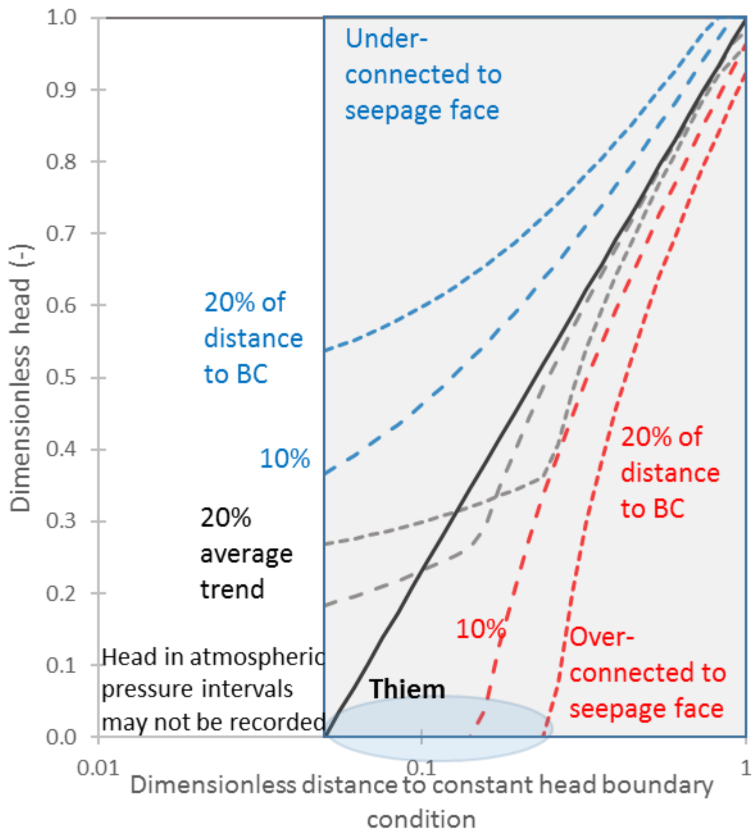

Fig. C.1 Dimensionless head versus dimensionless distance to constant head boundary condition. Red dashed lines show case of over-connected intervals. Blue dashed lines show under-connected intervals. Grey lines dashed show average of over and under-connected

This model indicates how connectivity effects might influence hydraulic head around an excavation and result in head patterns similar to that discussed by /KUL 02/, /PUS 03/ and /BLA 16/. Ideally fracture network simulations considering a range of network connectivity could be used to assess this proposed mechanism for skin effects in poorly connected fracture networks.

Appendix D Process characteristics

Tab. D.1 Groundwater degassing

Description	Degassing of groundwater resulting in two phase -flow conditions in excavation nearfield
Cause	Reduction of hydraulic pressure below “bubble point”
Process	Hydraulic (H) → flow and transport
Reversibility	Yes, in case of increasing pressure at excavation/borehole (dependent on groundwater gas saturation)
Timescale	Near instantaneous with drawdown but slow further dynamics depending of flow and subsequent pressure increase
Spatial scale	Likely to be very close to outflow (dependent on gas saturation, cp. Appendix A)
Repository relevance Operational phase	Potentially (see /JAR 00/ minimum gas content threshold 2-5%)
Repository relevance Post closure phase	Once pressure has recovered degassing will not be significant (gas maybe generated by corrosion of the waste)
Key parameters	Groundwater gas content, two-phase flow parameters and fracture flow geometry

Tab. D.2 Turbulent flow.

Description	Fluid flow in channels or rough fractures is no longer laminar and results in an additional pressure drop
Cause	High near-wellbore flow velocities during pump tests
Process	Hydraulic (H) → flow
Reversibility	Yes - dependent on flow velocity
Timescale	Instantaneous
Spatial scale	Dependent on fracture flow geometry
Repository relevance Operational phase	Yes
Repository relevance Post closure phase	Flow velocity will be much diminished post-closure
Key parameters	Fracture flow geometry and flow velocity

Tab. D.3 Capillary and evaporation barriers

Description	In partially saturated systems flow may be diverted around excavations
Cause	Drying and capillary forces
Process	Hydraulic (H) → flow
Reversibility	Yes, with wetting
Timescale	Slow
Spatial scale	Depends
Repository relevance Operational phase	Yes
Repository relevance Post closure phase	Yes, at Yucca Mountain
Key parameters	Two-phase flow parameters

Tab. D.4 Fracture normal closure

Description	Increased pressure in fracture results in fracture opening (-ve skin). Reduced pressure results in fracture closure (+ve skin)
Cause	Stress re-distribution due to excavation
Process	Geomechanical (M) → flow and transport
Reversibility	Yes, for small effective stress changes, large effective stress perturbations may result in permanent deformation
Timescale	Near instantaneous with stress change
Spatial scale	Likely to be close to excavation boundary
Repository relevance Operational phase	Yes
Repository relevance Post closure phase	Potentially - swelling of backfill and buffer will result in reloading of the rock and changes in stress
Key parameters	In situ stress, fracture stiffness and filling

Tab. D.5 Shear deformation

Description	Stress changes resulting in shear deformation and movement/creation of fracture filling materials
Cause	Excavation or pore pressure change
Process	Geomechanical (M) → flow and transport
Reversibility	No
Timescale	Near instantaneous with stress change
Spatial scale	Likely to be close to excavation boundary
Repository relevance Operational phase	Yes
Repository relevance Post closure phase	Yes
Key parameters	In situ stress, fracture shear strength and fracture filling

Tab. D.6 Grain scale disturbance at excavation surface

Description	Greater porosity and micro-cracking and increased surface area of reactive minerals at the opening surface
Cause	Borehole drilling or excavation
Process	Geomechanical (M) → transport
Reversibility	No
Timescale	At excavation
Spatial scale	Typically scale of mineral grains – can be greater in high stress environments
Repository relevance Operational phase	No
Repository relevance Post closure phase	Minimal
Key parameters	Excavation method and distribution of reactive mineral surfaces

Tab. D.7 Scale/connectivity effect

Description	Flow at the excavation/borehole scale is dominated by the performance of individual channels/fracture while far-field flow is controlled by network properties.
Cause	-
Process	Structural (S) → flow and transport
Reversibility	No
Timescale	Near instantaneous with flow
Spatial scale	Will depend on the scale and connectivity of the flowing features (channels/fractures)
Repository relevance Operational phase	Yes
Repository relevance Post closure phase	Potentially although flow velocity and effects related to convergent flow will be much diminished
Key parameters	Fracture flow geometry

Tab. D.8 Clogging of pores by precipitation

Description	Filling up pores and fractures with impermeable material
Cause	Precipitation due to geochemical imbalance in produced fluids
Process	Geochemical (C) → flow
Reversibility	No
Timescale	Slow
Spatial scale	Large scale
Repository relevance Operational phase	Unclear
Repository relevance Post closure phase	Yes
Key parameters	Mineralogical groundwater composition

Tab. D.9 Clogging of pores by fines

Description	Filling up pores and fractures with impermeable material
Cause	Production of fines in drilling fluids or release of clay flakes
Process	Mechanical (M) → flow and transport
Reversibility	No (?)
Timescale	Dependent on solids content an flow rates
Spatial scale	Pore scale
Repository relevance Operational phase	No
Repository relevance Post closure phase	No
Key parameters	Pore and particle sizes

Tab. D.10 Pore size distribution

Description	Varying transport velocities on a small-scale
Cause	-
Process	Structural (S) → transport
Reversibility	No
Timescale	Instantaneous
Spatial scale	mm- to cm-scale
Repository relevance Operational phase	No
Repository relevance Post closure phase	Yes
Key parameters	Pore size distribution and flow channel geometry

Tab. D.11 Advection opposing flow

Description	Reduction of diffusive flow
Cause	Water flow against direction of diffusion
Process	Hydraulic (H) → transport
Reversibility	Yes when flow decreases
Timescale	Instantaneous
Spatial scale	Depends on the rate (see Appendix B)
Repository relevance Operational phase	No
Repository relevance Post closure phase	No
Key parameters	Permeability, storage coefficient, porosity

Tab. D.12 Rock de-saturation

Description	Reduction of water flow due to phase obstruction
Cause	Ventilation-related dying of rock; “compartment” drainage if insufficient recharge; blasting gases forced into pores
Process	Hydraulic (H) → flow
Reversibility	Yes
Timescale	Days/weeks; instantaneous
Spatial scale	Meter-scale
Repository relevance Operational phase	Yes
Repository relevance Post closure phase	No
Key parameters	Two-phase flow parameters

Tab. D.13 Post-test artefacts

Description	Apparent reduction of diffusive transport
Cause	Various, e. g. capillary transport, continued diffusion
Process	Hydraulic (H) → transport
Reversibility	N/A
Timescale	Dependent on nature of artefact
Spatial scale	Dependent on nature of artefact
Repository relevance Operational phase	Depends on the introduced errors
Repository relevance Post closure phase	Depends on the introduced errors
Key parameters	Dependent on nature of artefact

**Gesellschaft für Anlagen-
und Reaktorsicherheit
(GRS) gGmbH**

Schwertnergasse 1
50667 Köln
Telefon +49 221 2068-0
Telefax +49 221 2068-888

Boltzmannstraße 14
85748 Garching b. München
Telefon +49 89 32004-0
Telefax +49 89 32004-300

Kurfürstendamm 200
10719 Berlin
Telefon +49 30 88589-0
Telefax +49 30 88589-111

Theodor-Heuss-Straße 4
38122 Braunschweig
Telefon +49 531 8012-0
Telefax +49 531 8012-200

www.grs.de

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