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Keywords: radioactive waste, bedrock geology, hydrogeology, hydrogeochemistry, paleohydrology, rock mechanics, fractured crystalline rock, Baltic Shield

Abstract

The proposed high-level radioactive waste repository sites at Olkiluoto and Forsmark share broadly similar geologic histories and regional settings. Despite differences in lithology, rock strength and patterns of brittle deformation, the sites show similarities in terms of hydrogeochemistry and hydrogeology. These similarities reflect a dominating influence of saline and brackish water intrusion during inundation by the postglacial Littorina Sea and Baltic Sea, followed by exposure to meteoric waters following postglacial uplift and transition to a Baltic coastal setting. Both sites also contain deep bedrock saline groundwater, though this is more evident at Olkiluoto than at Forsmark.

A comparative study of site descriptive models for the two sites identifies the following key differences that could potentially impact safety of a repository:

- Redox controls, buffering and biogeochemistry at proposed repository depths;
- Salinity gradients at and below proposed repository depths;
- Methane concentrations at and below proposed repository depths;
- Depths to which glacial water and Littorina water penetrated;
- Cation hydrogeochemistry and water-rock reaction;
- Pore water compositions in rock matrix;
- Rock fabric, secondary minerals and alteration with respect to radionuclide retention.
- Brittle deformation fabric differences on multiple scales that affect vertical hydraulic conductivity;
- Differences in apparent frequency of encountering water-conducting networks at proposed repository depths;
- Shallow bedrock hydraulic properties;
- Unique intrusive or dissolution features;
- Connectivity of site-scale models to regional-scale features.
- Mesoproterozoic rocks in vicinity and possibilities for human-intrusion scenarios;
- Rock stresses and bedrock strength and deformability at proposed repository depths;
- Thermal anisotropy.

These differences are all potentially significant to safety functions, but none are so severe that they clearly would have a direct, critical effect on the outcome of performance assessment calculations. In general, the effects of these differences would need to be evaluated in terms of secondary processes that affect safety functions.

Given the results of recent safety assessments based on the KBS-3 disposal concept, a primary part of the safety functions assigned to the geosphere is to provide a stable environment for the engineered barriers (waste package and buffer). Considering this, the differences between sites in terms of redox and salinity at depth, are of prime importance. Differences in vertical hydraulic conductivity are relevant for assessing the likelihood of maintaining favorable conditions under changing surface conditions, for example circumstances that could lead to infiltration of very dilute glacial meltwaters.

GEIER Joel, BATH Adrian, STEPHANSSON Ove. Olkiluodon, (Suomi) ja Forsmarkin (Ruotsi) kallioihin liitettyjen paikkamallien vertailu. STUK-TR 14. Helsinki 2012. 64 s.

Avainsanat: radioaktiivinen jäte, kallioperägeologia, hydrogeologia, hydrogeokemia, paleohydrologia, kalliomekaniikka, kiteinen rakoillut kallio, Baltian kilpi

Tiivistelmä

Olkiluotoon ja Forsmarkiin ehdolla olevat korkea-aktiivisen jätteen loppusijoituspaikat ovat geologisesti samankaltaisissa ympäristöissä. Huolimatta paikkojen litologiaan, kivien lujuuksiin ja hauraaseen deformaatioon liittyvistä eroista paikoilla on lukuisia hydrogeokemiallisia ja hydrogeologisia yhtäläisyyksiä. Yhtäläisyydet näkyvät syvien suolaisten vesien sekä Littorina ja Itämerestä peräisin olevien murtovesien läsnäolona kalliossa ja myös edelleen maankohoamisesta seuraavan meteoristen vesien tunkeutumisena kallioon.

Paikkojen vertailussa voidaan tunnistaa seuraavia avaineroja, joilla voi olla vaikutusta loppusijoituslaitoksen pitkäaikaisturvallisuuteen:

- redox olot ja biogeokemia ehdotetulla loppusijoitussyvyydellä
- suolaisuusgradientit ehdotetulla loppusijoitussyvyydellä ja syvemmällä
- metaanipitoisuudet ehdotetulla loppusijoitussyvyydellä ja syvemmällä
- glasiaali- ja Littorina vesien tunkeutumissyvyydet kalliossa
- kationihydrogeokemia sekä pohjavesi-kallio vuorovaikutukset
- eheän kallion huokosvesikoostumukset
- kiven kutous, sekundääristen mineraalien ja muuttuneisuuden vaikutus nuklidien pidättymiseen
- hauraat deformaatiorakenteet eri mittakaavoissa ja vaikutukset vertikaaliin vedenjohtavuuteen
- rakojen löytymisfrekvenssit, jotka kuvaavat vettä johtavaa rakoverkkoa loppusijoitussyvyydessä
- kallion hydrauliset ominaisuudet lähellä maanpintaa
- ehdokaspaikoille ominaiset fluidien tunkeutumisilmiöt ja mineraalien liukenemisprosessit
- hydraulinen kytkeytyneisyys paikkamittakaavan mallien ja alueellisten rakenteiden kesken
- ympäristön Mesoproterotsooiset kivilajiyksiköt ja ihmisen tunkeutumisskenaariot
- kivien jännitystilat, lujuus ja rikkoutuminen ehdotetulla loppusijoitussyvyydellä
- terminen anisotropia

Yhdelläkään luetelluista eroista ei ole niin huomattavia seurauksia, että niistä seuraisi suoria kriittisiä vaikutuksia turvallisuusperustelun laskelmiin. Erojen vaikutuksia tuleekin arvioida turvallisuustoimintojen täyttymiseen vaikuttavien prosessien kautta.

Geosfäärin tärkein turvallisuustoiminto on taata vakaa ympäristö rakennetuille päästöesteille (erityisesti jätepakkaukselle ja sen puskurille). Tämä huomioiden erot redox olosuhteissa ja suolaisuudessa loppusijoitussyvyydellä ehdokaspaikkojen kesken ovat erityisen tärkeitä. Kallion vedenjohtavuus on keskeistä suotuisten ominaisuuksien pysyvyydelle maanpäällisten olosuhteiden vaihdellessa. Erityisesti tämä koskee olosuhteita, joissa hyvin laimeat jäätikön sulamisvedet tunkeutuisivat syvälle geosfääriin.

Contents

1 Introduction

1.1 Background

Olkiluoto and Forsmark have both been proposed as sites for geological disposal of high-level radioactive waste (spent fuel). The two sites are at different stages in terms of the licensing and construction process.

For Olkiluoto, in 2001 Finland's government granted a favorable Decision in Principle on Posiva Oy's application to locate a repository at Olkiluoto. According to Posiva (2008), Posiva aims to submit an application for a construction license for the proposed disposal facility by the end of 2012. Construction has already commenced (as of autumn 2004) on the ONKALO underground rock characterization facility, which will serve as part of the access to the proposed repository, if the construction license application is approved.

The Forsmark site was selected by the Swedish Nuclear Fuel and Waste Management Company (SKB) in June 2009 as the site for a final repository, after detailed site investigations both at Forsmark and at a second candidate site, the Laxemar site (in the Oskarshamn municipality). A license application for underground construction at Forsmark was submitted to Sweden's government in March 2011, with the safety assessment SR-Site (SKB, 2011) as supporting documentation.

Both sites are near working nuclear reactors and repositories for lower-level nuclear waste. The west end of Olkiluoto houses two working reactors and a third reactor under construction, as well as the VLJ low- and intermediate-level waste repository (Figure 1). Forsmark has three reactors to the northwest of the planned underground facility

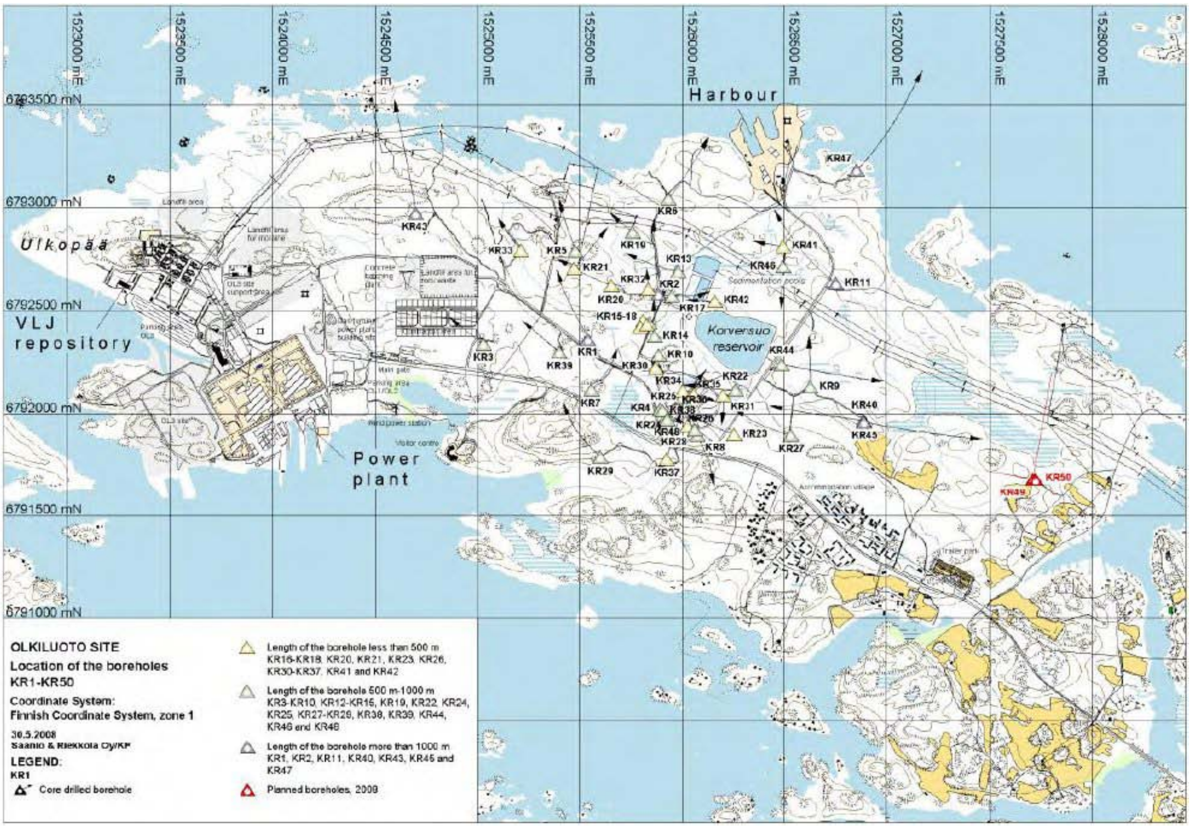


Figure 1. Olkiluoto site map showing locations of deep drillholes (from Posiva 2009-01, Figure 1-1). The size of the grid squares is 500 m × 500 m.

(Figure 2); the SFR low- and intermediate-level waste repository is to the northeast of the site, accessed via a causeway to an offshore island.

1.2 Purpose and objectives

The purpose of this review is to produce background information for STUK's safety appraisal work, and to help STUK to prepare for potential public discussions that may start as license applications are handled and evaluated in both countries.

The objectives are:

- to identify the similarities and especially the differences between the sites,
- to prioritize the differences according to their safety relevance, and
- to identify the probable sources of uncertainty.

These objectives are addressed first by comparing data availability (Section 2), then each of a series of geoscientific disciplines (geology, hydrogeology, hydrogeochemistry, and rock mechanics) in Sections 3–6, followed by an integrated discussion in Section 8.

1.3 Basis for review

The site descriptive models (SDMs) that form the primary basis for this review are:

- Olkiluoto site-descriptive model version OSD 2008 (Posiva 2009-01); OSD 2011 was not yet available at the time of this review;
- Forsmark site descriptive model version SDM-Site (SKB, 2008).

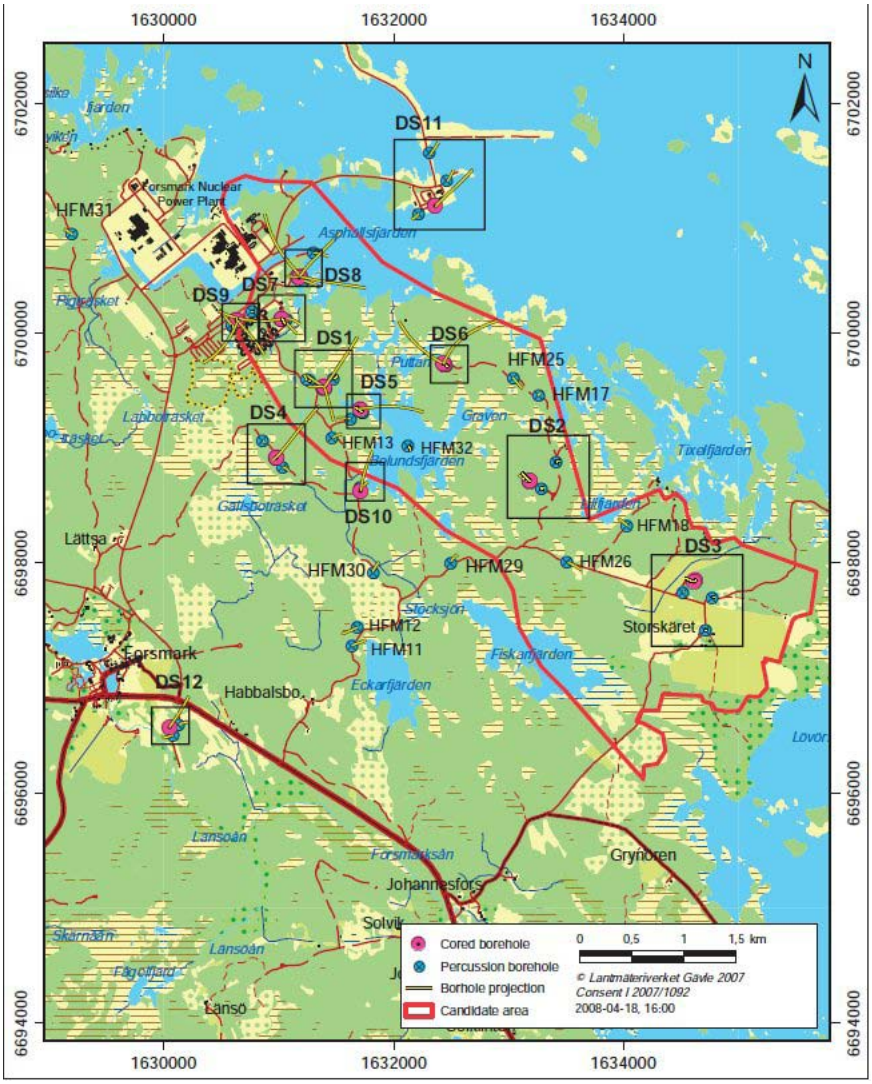


Figure 2. Forsmark site map showing locations of drillholes and percussion-drilled boreholes (from SKB TR 2008-05, Figure 2-1).The projection of the boreholes on the ground surface due to their inclination is also shown.

Table 1. Selected differences in nomenclature used for the Olkiluoto and Forsmark sites.

Olkiluoto	Forsmark
drillhole	core-drilled borehole
borehole	percussion-drilled borehole or soil borehole
brittle deformation zone	brittle deformation zone or fracture zone
hydrogeological zone	deformation zone (in hydrogeological model)

The prioritization according to safety relevance relies in part upon on expert judgment, as the authors have not had opportunity to review a safety evaluation based directly on either OSD 2008 or SDM-Site. Preliminary safety evaluations based on earlier versions of these SDMs have been presented in RNT 2008 (Nykyri *et al.*, 2008) and the SR-Can safety assessment (SKB, 2006), and help to inform this expert judgment. SKB's safety evaluation SR-Site for the Forsmark license application, has been published but the authors of the present report have not formally reviewed those reports. However, the authors have reviewed the SDM-Site reports which are referenced as part of the license application by SKB.

1.4 Nomenclature

Some differences in nomenclature are encountered in comparing the SDMs between Forsmark and Olkiluoto. This review uses the Olkiluoto terminology as summarized in Table 1.

2 Scope and support for site descriptive models

A comparison of the scope and level of support for SDMs is summarized in Table 2 at the end of this section. The following subsections give additional comments.

2.1 Area and depth of site descriptive models

Both sites are described to approximately 2 km depth, although drillhole investigations are generally limited to depths of 1 km or less.

Olkiluoto Site Description 2008 (OSD 2008) covers the whole area of the island, about 10 km². The geological site model includes some adjoining marine areas for a total area of roughly 18 km². A smaller area covering the footprint of the proposed repository is referred to as the Well-Characterised Area. The underground rock characterization area ONKALO with its access tunnel, research and demonstration area and the central area of the proposed repository is located in the Well-Characterised area.

SDM-Site Forsmark covers a total area of about 12 km². The target area, *i.e.* the proposed repository footprint and immediate surroundings in the north-western part of the candidate area, is about half that area and is the location for most of the deep drillholes.

2.2 Surface exposure

Surface exposure of the bedrock is limited by Quaternary deposits at both sites. Outcrops tend to be on higher ground as lower areas of the bedrock surface tend to be buried under recent accumulations of sediments and organic materials. At both sites, investigation trenches have been used to increase the area of rock that can be studied. At Forsmark the possibility to clear trenches has been restricted for ecological reasons. Most of the trenches are restored after mapping.

2.3 Surface-based geophysics and lineament interpretations

An extensive suite of surface-based geophysics and remote-sensing methods were used at both sites to support descriptions of the bedrock geology and to identify potential deformation zones, as summarized in Table 2.

For both sites, extensive Quaternary cover limited the identification of lineaments from topography. LIDAR mapping, which was used for identification of minor deformation zones down to a length scale of 100 m at the Laxemar site, was judged to be unsuitable for Forsmark for the same reason.

For Forsmark, access to high-precision bathymetric data improved detection of lineaments in the seabed. However, even with these data, the interpreted lineaments are noticeably more sparse offshore than onshore. For Olkiluoto, the available acoustic (echo-sounding) bathymetric data were of noticeably lower resolution than the on-land topographic data. This limited resolution might partly explain why relatively few high-confidence lineaments were recognized in the seabed around Olkiluoto, and why only four brittle fault zones are interpreted as extending more than 100 m beyond the land areas into the seabed. This limits connectivity to the regional fault zones that bound the model area.

At Forsmark, a high-resolution ground magnetic survey was key for identifying potential steeply-dipping deformation zones down to a length scale of 100 m. Seismic reflection (25 km of profiles) and seismic refraction (23.2 km of profiles) surveys were key to identifying potential sub-horizontal to gently-dipping deformation zones at depth.

At Olkiluoto, airborne magnetics of resolution comparable to those used at Forsmark were not performed until 2008 (Aaltonen *et al.*, 2010), and thus

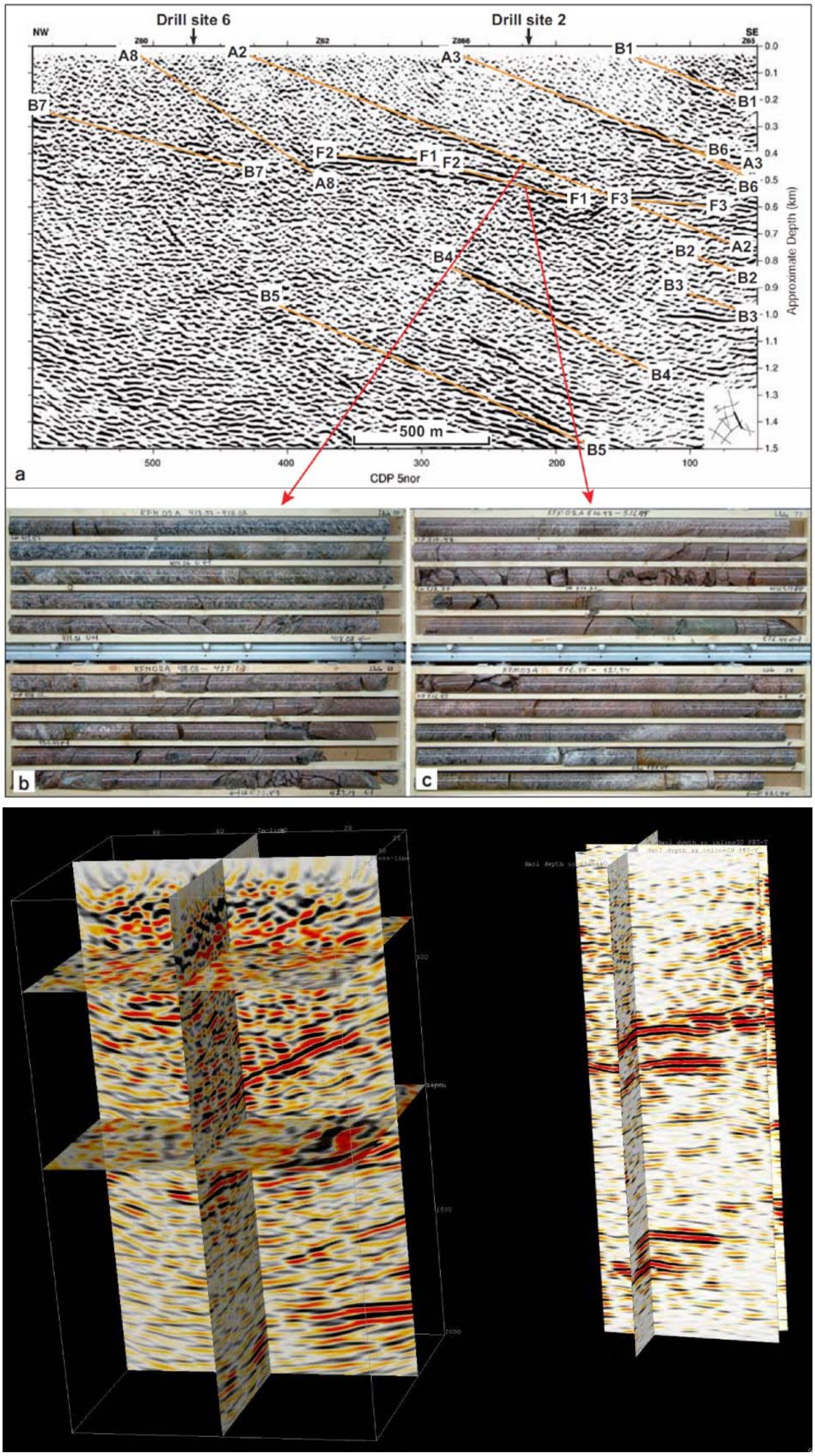


Figure 3. Main impressions of reflectors from 3-D seismic reflection studies. A, Forsmark site showing the shallow dipping deformation zones and the fracturing in the core box for deformation zone A2 (left bottom box) and F1 (right). B, Olkiluoto site showing reflectors from the 2006 survey (right) and the 2007 survey (left). After SKB (2008) and Posiva (2009a).

were not available for OSD 2008. Lower-resolution airborne magnetics were used to identify lithologic boundaries and to detect potential steeply-dipping deformation zones on larger scales. As for Forsmark, reflection seismic and refraction seismic campaigns have been used to identify potential sub-horizontal to gently-dipping deformation zones at depth. A 3D seismic pilot study has been carried out, giving more detailed data for an approximately 1.15 km × 1.05 km × 1 km deep block of the model.

3-D reflection seismic investigations have been conducted at both sites and have been of great value in determining the major deformation zones (Fig. 3). At both sites the seismic studies were performed in two stages. The second stage was 3-D seismic reflection studies. At Forsmark the results gave a clear picture of the gently dipping deformation zones dipping to southeast. Several of the zones were later confirmed in the core-drilled boreholes. The proposed repository at Forsmark is located in the footwall of the most prominent gently dipping zone, called A2. For Olkiluoto the results of the seismic studies provided direct information on the dipping reflection structures and gave also important information of the vertical deformation zones.

2.4 Drillholes

Both sites have been investigated by core-drilling to depths of about 1 km. At Olkiluoto, 48 deep drillholes were finished in time for OSD 2008, mainly in the central and western parts of the island. Subsequently, additional holes have been drilled in the eastern part of the island, including OL-KR49 and OL-KR50 which were in progress at the time of OSD 2008. At Forsmark there are fewer deep drillholes (18) but these give somewhat more uniform coverage of the site, and include five supplementary “B” drillholes to characterise the shallow bedrock which is missed by deeper boreholes using the telescopic core-drilling technique.

In addition, many shallower boreholes (percussion-drilled holes) or shallow drillholes have been completed at both sites. At Forsmark, 19 shallow boreholes, ranging from 127 m to 301 m in depth, were completed in support of SDM-Site. At Olkiluoto, 36 shallow (10–20 m) drillholes were drilled to supplement the bedrock mapping; an additional 16 shallow drillholes (14–36 m) which were drilled within the site area in the 1970s were re-logged in 1990.

For Olkiluoto, additional data are available from pilot holes along the ONKALO ramp, accounting for 1257 m of the 3415 m of chainage by the time of OSD 2008.

2.5 Underground mapping

The availability of geologic mapping data from underground in the ONKALO facility is a major difference in data availability between the two sites. As of September 2008, the access tunnel had reached a length of 3100 metres, corresponding to a depth of approximately 300 m. This allows mapping of unweathered rock surfaces, including intersections of the tunnel with brittle deformation zones which are often strongly affected by weathering at the surface. This access has also allowed testing of the structural geological model’s extension at depths of up to 300 m.

Table 2. Comparison of scope and support for site descriptive models (selected aspects).

Aspect	Olkiluoto	Forsmark	Implications
Volume of SDM	10 km² × 2 km deep	12 km² × 2 km deep	Similar scales for detailed investigations
Natural surface exposure of bedrock	Limited (4%)	Limited (<10%)	Uncertainty in fracture size distribution for scales larger than 5–10 m
Cleared areas for additional bedrock surface mapping	13 trenches with a total length of ca. 3700 m and widths of 0.5 m to 5 m; two outcrops nominally 30 m × 40 m were also mapped in detail	9 areas with a total area of about 3150 m²	Improved but still limited exposure, particularly for fracture sizes larger than 5 m to 10 m
Topographic lineament interpretations	Regional-scale covering the Southern Satakunta area (Paananen and Kuivamäki, 2007); local-scale (Kuivamäki et al., 2005)	Regional-scale and site-scale based on digital elevation model	
Bathymetric data used in lineament interpretations	Intermediate-precision echo-sounding data for bathymetry	High-precision bathymetry	Affects detection of lineaments in seabed, and thus connectivity of local model to boundary conditions
Magnetic surveys	Intermediate-resolution (50-100 m spacing) airborne surveys; a higher-resolution survey was not completed in time for OSD 2008	High-resolution ground survey covering 11.1 km² area used in SDM-Site to identify minor deformation zones	Combined with limited bedrock exposure, affects identification of minor deformation zones on scales < 1 km
3-D Reflection Seismics	100–1000 m depth range of gentle dipping and vertical deformation zones. 2007 studies in the eastern area.	Confirmation and areal extension of the SE gently dipping deformation zones in the southern part of the investigation area	The 3-D seismic reflection studies conducted at both sites improved the knowledge of the extent, orientation and character of the deformation zones.
Subsurface mapping	Tunnel mapping at ONKALO	None within site boundaries; older data from shallow depths at SFR and the inlet and outlet tunnels of the reactors.	Checking of geological model at depth; complementary data on fracture size and orientation distributions
Deep drillholes	48 (300 m to 1000 m length) with a total length of 22 960 m in time for OSD 2008; concentrated in the central part of the site	18 total for SDM-Site with a total length of 17 532 m (12 telescopic holes 500–1000 m deep, 6 standard holes 100–800 m, including 5 “B” holes focused on upper 100 m of the bedrock at telescopic drilling sites). Distributed across site but focused mainly on NW part of site.	More concentrated drilling pattern at Olkiluoto provides more intensive characterisation of small area, but less information on effective boundary conditions and large-scale spatial variation. “B” holes at Forsmark improve understanding of shallow bedrock.
Data for bedrock permeability	Posiva Flow Log, injection tests in drillholes; in-situ pressures	Posiva Flow Log, injection tests in drillholes; in-situ pressure measurements sparse due to equipment problems	In-situ groundwater pressure data provide additional constraint for hydrogeological model calibration.
Deep groundwater chemistry	Sampling and measurements using PAVE tool and multi-packer monitoring installations, also sampling at groundwater stations and pilot holes in ONKALO.	Sampling and measurements by downhole CHEMMAC tool and other double-packer downhole pumping and sampling tools and multi-level monitoring installations.	Similar sampling strategies and technologies in both cases, achieving varying degrees of success in obtaining reliable samples.
Rock stress measurements	Methods used for Forsmark, plus Kaiser Effect and shaft convergence measurements and overcoring around periphery of openings and stress integration	Hydraulic and sleeve fracturing, hydraulic pressurization of pre-existing fractures, overcoring, analysis of core disking and wellbore breakouts	Combination of Kaiser Effect measurements plus more usable overcoring stress measurements gives increased confidence in Olkiluoto stress model vs. that for Forsmark.

3 General geology

3.1 Bedrock origins

The rocks in the vicinity of both sites were formed mainly in the Paleoproterozoic era, and show evidence of polyphase deformation during the Fennian orogeny 1900 Ma to 1850 Ma, peaking around 1890 Ma, and the subsequent Svecobaltic orogeny 1840–1800 Ma (Lahtinen *et al.*, 2005).

The youngest rocks exposed on land near Olkiluoto are Mesoproterozoic in age; these include rapakivi granites which intruded in an extensional setting around 1590–1540 Ma (Rämö and Haapala, 2005), sandstones which were deposited in a coastal sedimentary basin that apparently opened in the same extensional episode continuing to about 1300 Ma, and finally olivine diabase dykes and sills 1270–1250 Ma in age during the initial rifting between the Baltica and Laurentia cratons. These Mesoproterozoic rocks are generally 5 km or more outside of the site boundaries. Younger sedimentary rocks and limestones (Cambrian to Ordovician in age) are found offshore in the Bothnian sea basin.

Rocks of Mesoproterozoic or younger ages have not been found at Forsmark or in the immediate vicinity. Sedimentary basins of Vendian to Early Palaeozoic age are found offshore to the north and east in the Bothnian sea basin, and are likely related to the sedimentary rocks found offshore of Olkiluoto in terms of general age and extensional setting. Remnants of Jotnian sandstones are still found locally in the sea well to the NE of Forsmark, in the deepest depressions in the older bedrock surface (Tirén and Beckholmen, 2009).

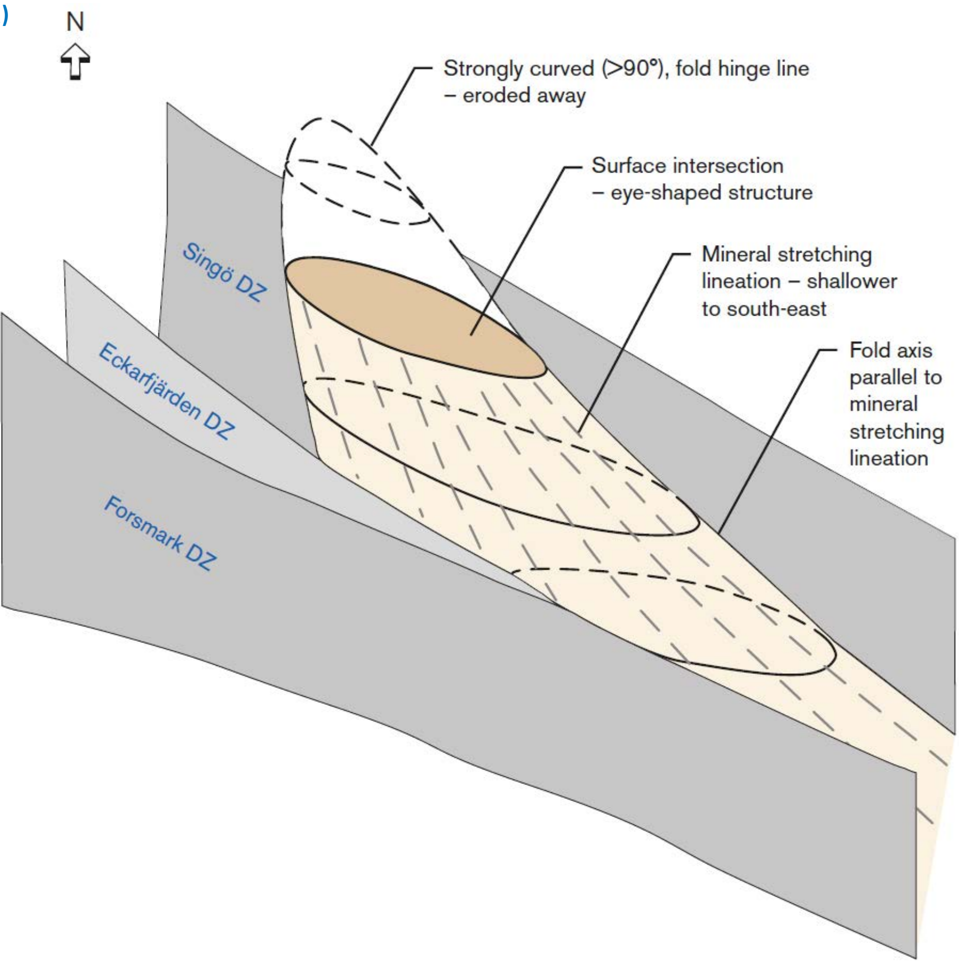
3.2 Structural setting

The proposed repository site at Forsmark is situated in a shear lens between three NW- to WNW-striking, anastomosing regional deformation zones (the Singö, Forsmark and Eckarfjärden deformation zones). The target volume for the repository is in the footwall of a stack of gently SE-dipping fault zones. The target volume is bounded by the limbs and hinge of a steeply dipping synform, which helps to give confidence in downward projections of the lithology. A conceptual model of the fold structure in the centre of the lens and the three regional deformation zones are presented in Figure 4a. The surface interception of the tectonic lens is indicated with brown color in the figure. Lineation of the minerals in the fold structure is indicated by short lines. The hinge of the fold structure is located just north of the proposed repository target volume.

Like Forsmark, the proposed repository site at Olkiluoto is bounded by two regional deformation zones, the Selkänummi and Liikla shear zones; these strike E to ENE, see Figure 4b. The northern part of the Olkiluoto site north of shear zone SNSZ is dominated by E-W striking tonalitic-granitic-granodioritic (TGG) gneiss units showing typical D_2 plastic deformation. The central domain located between the two shear zones is characterized by D_3 deformation showing pervasive foliations and migmatite structures. In the southeastern part of Olkiluoto area the bedrock is dominated by relict plastic D_3 structures overprinted by later deformation phases. 3-D reflection seismic studies indicate a stack of gently to moderately SE-dipping deformation zones in the southernmost domain which are interpreted as thrust faults.

The main tectonic mechanisms for regional stresses (east-west ridge-push from opening of the Atlantic Ocean, and north-south compression from the Alpine orogeny) are similar at the two sites and are expected to continue through the period in which repository performance is of concern. Uplift of Fennoscandia due to post-glacial isostatic rebound continues to affect both sites. Both sites could experience repeated ice loading and isostatic depression in the next glacial period, although pos-

(a)



(b)

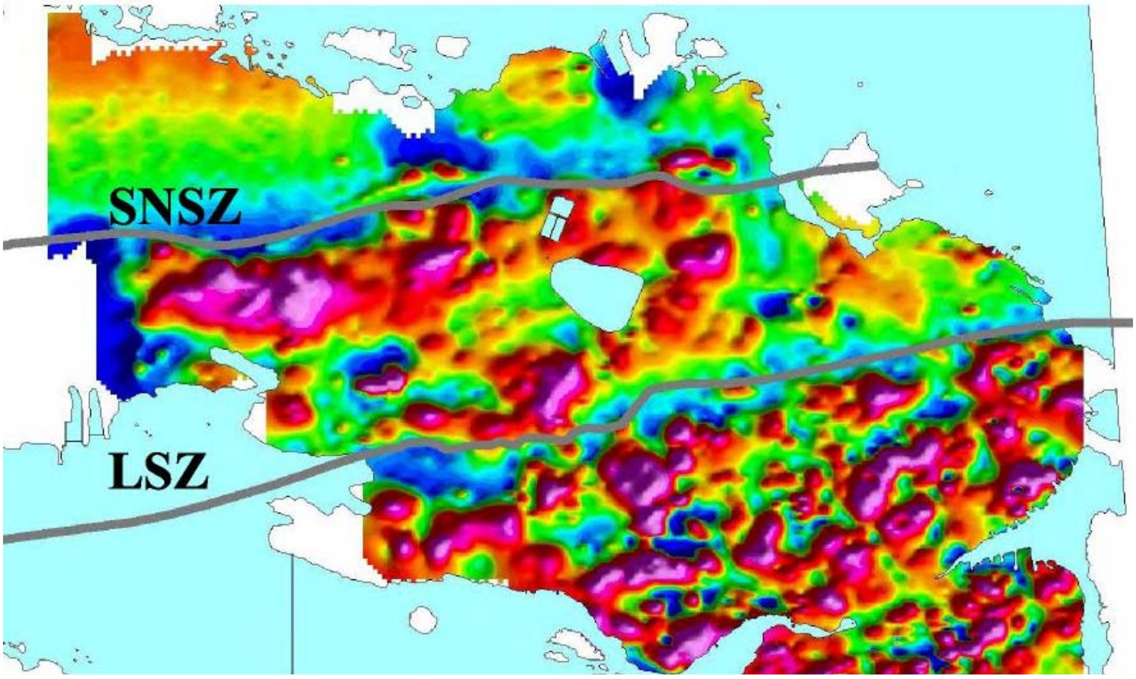


Figure 4. Tectonic setting and major deformation zones at Forsmark **(a)** and Olkiluoto **(b)**. A, Model of large-scale stretch folding of the tectonic lens of meta-granites at Forsmark and its location between the three major deformation zones: Singö, Eckarfjärden and Forsmark. B, Three major structural domains separated by the Selkänummi shear zone (SNSZ) and Liikla shear zone (LSZ). After SKB (2008) and Posiva (2009).

sibly to different degrees/durations and at different stages of the glaciation. The thermal loads from the repositories, and thermal boundary conditions from permafrost and ice cover, will also affect rock stresses at both sites, over similar periods although possibly to varying degrees/durations. During the peak of the ice load the vertical rock stress becomes the maximum principal stress. At the late stage of deglaciation the stress orientation and magnitude change and the vertical stress becomes the intermediate or least principal stress.

3.3 Lithology and rock mineralogy

The rock at Forsmark is dominantly a medium-grained (meta) granite which has been affected by penetrative ductile deformation at mid-crustal depths and under high-temperature metamorphic conditions 1.87 to 1.86 Ga. Amphibolite and fine- to medium-grained granitoid were intruded syntectonically as dykes and minor bodies. Locally, at least the amphibolites gave rise to conspicuous alteration (albitization) in the older granitic rocks. Ductile deformation with folding continued to affect the younger intrusive rocks, including amphibolite, under lower metamorphic conditions, prior to 1.85 Ga. Subsequently, until at least 1.8 Ga, the ductile strain continued to affect the bedrock, predominantly at the margins of the tectonic lens along discrete zones (Section 3.1). Borehole data indicate that the tectonic lens is a major geological structure that can be traced from the surface down to at least 1,000 m depth.

The bedrock of Olkiluoto comprises high-grade metamorphic rocks that have been migmatised so that they contain quite substantial proportions of granitic rock. The lithologies are sub-divided into: (i) migmatitic gneisses, the main rock type (about 64%), which are most frequently veined; (ii) tonalite-granodiorite-granite gneisses (about 16%), either foliated mica gneiss or non-foliated granitic gneiss; (iii) pegmatitic granites (about 20%), coarse-grained felsic rocks occurring as veins and irregular masses; (iv) diabase dykes, dark thin pervasively altered material. Dominant minerals in the migmatitic gneisses are generally quartz (20–45%), plagioclase (10–30%), biotite (10–40%) and K-feldspar (<20%). K-feldspar is more abundant in the granitic lithologies at Olkiluoto. Other minerals in the gneisses include hornblende, pyroxene, cordierite, sillimanite and garnet. The variety of sedimentary rock precursors of the migmatites account for distinct groupings according to rock geochemistry with about 27% of the lithologies having relatively high P contents (>0.3% P_2O_5) and about 10% having relatively higher Ca content.

The bedrock at Forsmark has been described in terms of three major rock groups: (i) biotite-bearing medium-grained metamorphosed granite/granodiorite tonalite, dominant in the target area, some of it aplitic with amphibolite dykes, some albitized, also some ultramafic rock (gabbro, diorite) though this occurs mostly outside the candidate area; (ii) fine- to medium-grained granodiorite/tonalite/(granite) occurring as lenses and dykes in the metagranite; (iii) fine- to medium-grained granite/aplite, with some pegmatite, occurring as discordant dykes and other minor bodies. The key structural characteristic of bedrock in the target area is that it is part of a ‘tectonic lens’ which has lower ductile strain, and thus is more folded and lineated, and is surrounded by anastomosing rock with higher ductile strain and foliation. The metagranite group constitutes 75±5% of the target rock volume (to 1000 m depth) with amphibolite and other mafic rocks comprising another 5±1%, the granodiorite/tonalite group constitutes 4±3%, and fine- to medium-grained granite/aplite/pegmatite constitutes 14±5%.

Dominant minerals in the metagranite at Forsmark are plagioclase (24–64%), quartz (28–46%), K-feldspar (0.2–36%) and biotite (1–8%), see Figure 5. Minor minerals include epidote, chlorite, titanite, allanite, calcite (<0.08%) and opaque minerals (0.1–0.5% of which a major part may be pyrite). Mineral composition of the fine- to medium-grained granodiorite/tonalite/(granite) is similar but with less quartz, higher biotite (2–19%) and/or substantial hornblende (0–25%) in some samples, and more calcite (up to 0.25%).

Whole-rock geochemical compositions for Forsmark bedrock are essentially as expected for these lithologies. Phosphorus average contents for the two main rock groups are 0.04 and 0.12±0.09 wt% P_2O_5. One noteworthy anomaly is the uranium contents of the fine- to medium-grained granite/pegmatite group which are occasionally anomalously high (1–62 ppm). Uranium contents of the two main rock groups are normal at 2–9 ppm.

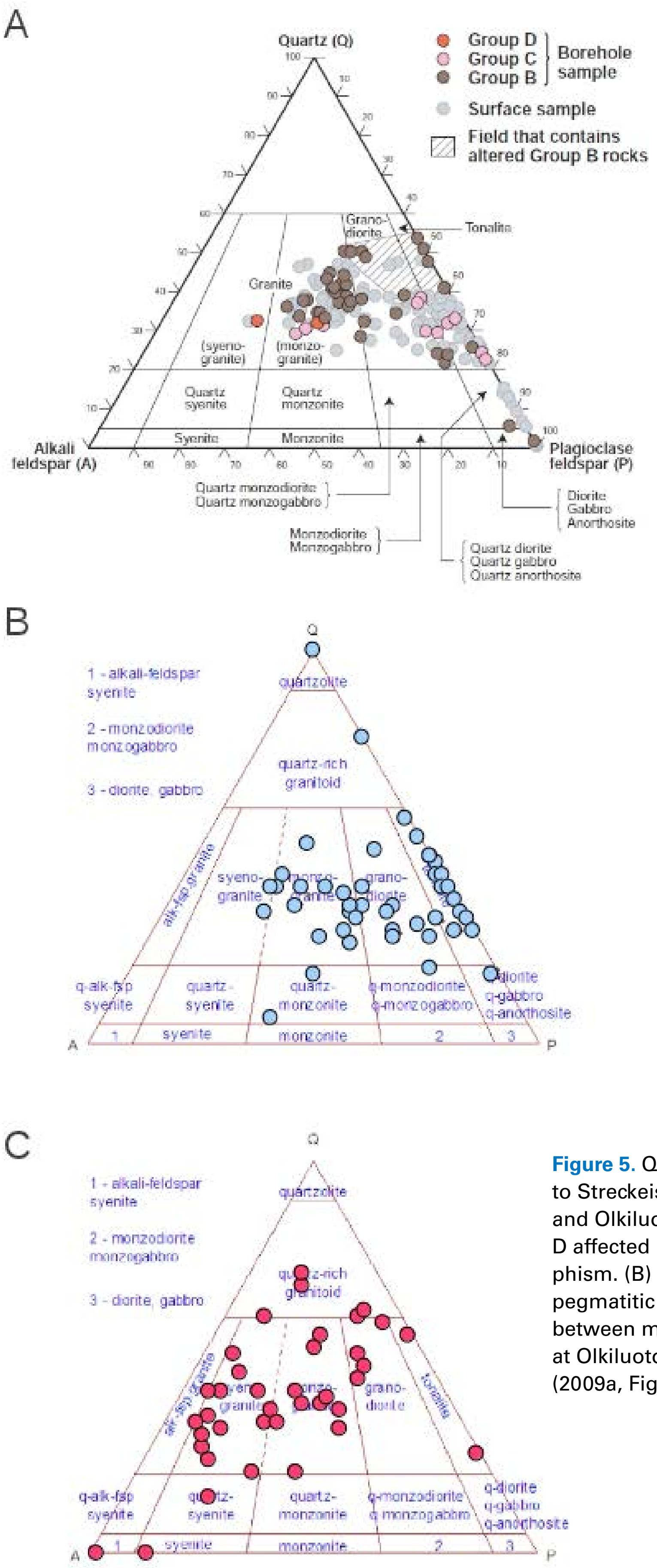


Figure 5. QAP classification of rock samples according to Streckeisen (1974) of the main rocks at Forsmark and Olkiluoto. (A) Forsmark, for rock groups B, C and D affected by ductile deformation and metamorphism. (B) Olkiluoto for TGG gneisses. (C) Olkiluoto for pegmatitic granites. Notice the similar composition between meta-granites in Forsmark and TGG gneisses at Olkiluoto. After SKB (2008, Figure 5.5) and Posiva (2009a, Figure 4-16).

3.4 Fracturing

For both sites, a stochastic discrete-fracture network (DFN) approach is used to model the fractures in the bedrock outside of the identified brittle deformation zones. The geological DFN (Geo-DFN) models are specified in terms of a stochastic process for the location of fracture centers and fracture intensity, and probability distributions for fracture size (disc radius) and fracture orientation (pole vector).

The overall fracture intensity for the proposed repository target volume is higher at Forsmark than at Olkiluoto, but this includes many fractures that are sealed. When just open fractures are considered, the intensity for Forsmark is lower, see Figure 6a. Hence larger volumes of very low-permeability rock can be expected for the target volume at Forsmark.

Fracture sets have been deduced primarily on the basis of fracture orientation. Both sites show three main sets, one of which is nominally horizontal while the other two are nominally vertical. The horizontal set at proposed repository depth is proportionally much stronger at Olkiluoto (Buoro *et al.*, 2009, p. 52) than at Forsmark (SKB, 2008 p. 116), both before and after correcting for sampling orientation bias, even when just data from boreholes (*i.e.* excluding ONKALO tunnels and outcrops) are considered.

At Forsmark, the subvertical sets are nominally NE- and NW-striking, with the NE-striking set dominant (Fig. 6a). At Olkiluoto, the subvertical sets are nominally N-S and E-W striking, with the N-S set being stronger (Table 3 and Figure 6b). A horizontal set of fractures is prominent at both sites. Many of the horizontal fractures belong to the sheet fractures generated during stress relief from repeated deglaciations.

The major fracture sets mapped in the first 2400 m chainage of the ONKALO tunnel are listed by orientations in Table 3. The fracture pole concentration contours for all mapped fractures in the tunnel and interpreted set windows for lower hemisphere plot is presented in Figure 6b.

Investigation of fracture location processes has included both simple Poisson processes (uniformly random in three dimensions) and fractal models which can produce more strongly clustered DFN simulations than are expected with a simple Poisson process. A small but significant degree of fractal clustering is indicated by the DFN analysis for both sites.

Another important aspect of fracture location is whether fractures are correlated to nearby deformation zones, outside of the borehole or tunnel intervals where they are recognized as belonging to the “damage zone” or zone of influence for the deformation zone. For Forsmark, strong significant statistical differences were found, but this finding was not propagated in the DFN models for SDM-Site. For Olkiluoto, such an analysis has not been presented.

The fracture size distribution is deduced based on fracture trace lengths measured on outcrops and (in the case of Olkiluoto) in tunnels. Uncertainty regarding large fractures (greater than 5–10 m in length) is high at both sites, due to the limited surface exposure, and also due to the uncertain applicability of surface observations for the rock at proposed repository depths. At Olkiluoto, it has been recognized that this uncertainty persists even with data from mapping of the shaft and ramp at the ONKALO facility, due to the limited size of underground tunnels. Hence for both sites, alternative forms of the size distribution have been tested which yield different expectations for the frequencies of large-scale fractures.

3.5 Fracture mineralogy

Calcite, clays and sulphides are common as fracture minerals at all depths at Olkiluoto. The main gouge-fillings in open fractures seen in the ONKALO tunnel are quartz, chlorite, illite, kaolinite, montmorillonite and calcite. Coatings on surfaces of open fractures are typically 0.3–0.4mm thick. A study of secondary minerals in transmissive fractures down to 480 m depth at Olkiluoto, focused primarily on the major sub-horizontal fracture zone HZ19, found mostly calcite coatings and fillings plus clays (kaolinite, illite, chlorite) and pyrite. Several generations of calcite have been identified, predominantly of hydrothermal origin, and only a minor proportion is interpreted to be of low-temperature recent origin. Uranium contents of the fracture calcites is reported to be <0.7ppm.

The most common fracture minerals at Forsmark are chlorite, calcite, laumontite/epidote/prehnite, sulphides and iron oxides. Chlorite and calcite form discrete irregular coatings on fracture surfaces, whereas pyrite, where it occurs, is scattered unevenly as small discrete crystals. Relative

Table 3. Major fracture sets mapped in the first 2400 m chainage of the ONKALO tunnel.

Fracture Set	Dip	Dip Direction	Corresponding Strike	Nominal Orientation
1	08°	065°	N 25° E	subhorizontal
2	89°	081°	N 09° E	N-S striking, subvertical
3	85°	359°	S 89° W	E-W striking, subvertical
4	32°	135°	N 45° E	NE striking, gently dipping SW

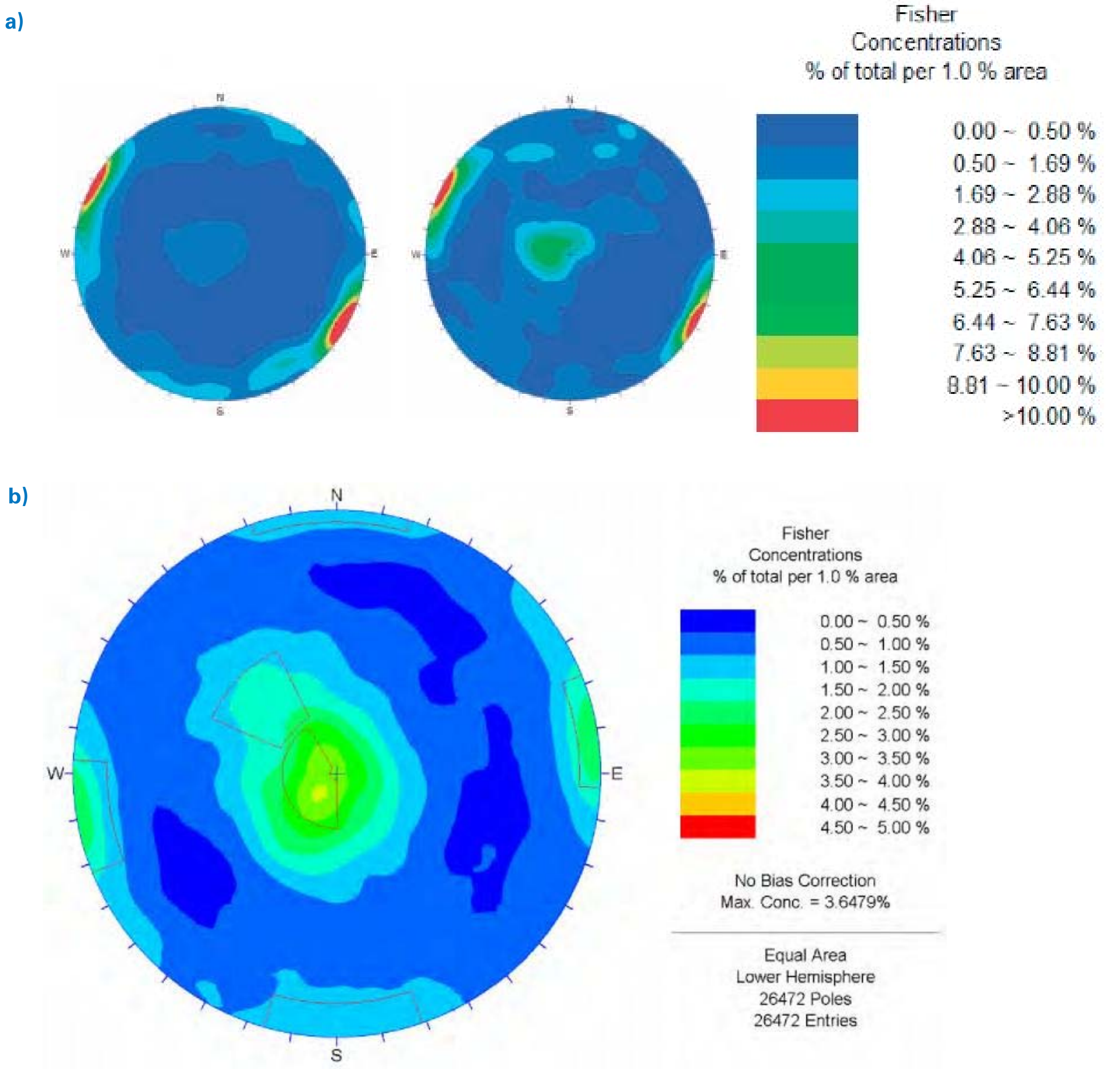


Figure 6. a) Orientation of fractures in borehole KFM06A in Forsmark, plotted as fracture poles (perpendiculars to the fracture planes) and contoured according to pole concentration on equal-area, lower-hemisphere stereonets. The left stereonet includes all 1593 fractures while the stereonet to the right includes just 360 open and partly open fractures. **b)** Fracture pole concentration contours for all fractures mapped in the first 2400 m chainage of the ONKALO tunnel. Lower hemisphere, equal area plots. After SKB (2008) and Posiva (2009). Note that fracture strike directions, as discussed in the text, are rotated by 90 degrees from the azimuths of the poles. Points near the perimeter of each stereonet represent steeply inclined fractures, while points near the center represent subhorizontal fractures.

Figure 7. Examples of horizontal cross-sections through simulated fracture populations based on geological DFN models for Olkiluoto and Forsmark. Upper plot shows fracture traces from a simulated 20 m × 20 m fracture trace map representing Olkiluoto outcrop OL-TK11, with colors indicating fracture sets: Set 1 in red is subhorizontal set; Set 2 in green is N-S striking set; Set 3 in blue is E-W striking set (from Tuominen et al., 2006, Figure 6-1). Lower plot shows fracture traces in a simulated plane through a 50 m × 50 m × 50 m cubic volume, based on one alternative DFN model for fracture domain FFM01 at Forsmark, with colors indicating fracture sets as shown in the legend, SH = subhorizontal (from SKB, 2008, Figure 5-40). Note that these simulations represent fracture domains at different depths for the two sites.

abundances of fracture minerals in sealed fractures are:

calcite (40%) >
chlorite (38%) >
laumontite (21%) >
hematite (4%) >
quartz/adularia/prehnite/pyrite/epidote/clays.

Relative abundances in open fractures are:

chlorite (62%) >
calcite (42%) >
clays (21%) >
pyrite (10%) >
hematite (9%) >
quartz/laumontite/prehnite/adularia.

3.6 Rock alteration

Hydrothermal alteration of bedrock at Olkiluoto is interpreted to have occurred in relatively low temperature conditions (ca. 300 to <100ºC). Four types of alteration have been identified: (i) formation of clays, mainly illite and kaolinite; (ii) sulphide mineral formation; (iii) calcite formation; (iv) quartz/sericite/epidote formation. Hydrothermal hematite has not been explicitly reported as identified at Olkiluoto (Section 4.4.4 in Posiva, 2009), in contrast to the case for Forsmark. Drillcore logging has suggested that the distribution of alteration is pervasive and fracture-controlled to roughly similar degrees, except for quartz/sericite/epidote alteration which is mostly pervasive. Overall, about 17% of total core length logged at Olkiluoto has been identified as 'altered'. In general, the porosity of altered rocks is higher than that of fresh bedrock; typical values are >0.5% and <0.5% respectively.

The hydrothermal alteration at Olkiluoto is most likely associated with the intrusion of the rapakivi granites at ca. 1.5 Ga ago. Figure 8 presents a conceptual illustration of the different hydrothermal processes from a granitic magma intruding from below and causing upflow of heat and fluids. A similar process can be anticipated for Forsmark in conjunction with the intrusion and later cooling of the Singö granite (ca.1,7 Ga in age) immediately east of Forsmark now visible on the island of Gräsö and on some of the small islands between Gräsö and Forsmark (Söderlund *et al.*, 2008).

Red staining of fracture surfaces and/or of the fracture-filling minerals is the most common type of hydrothermal alteration at Forsmark. In addition to

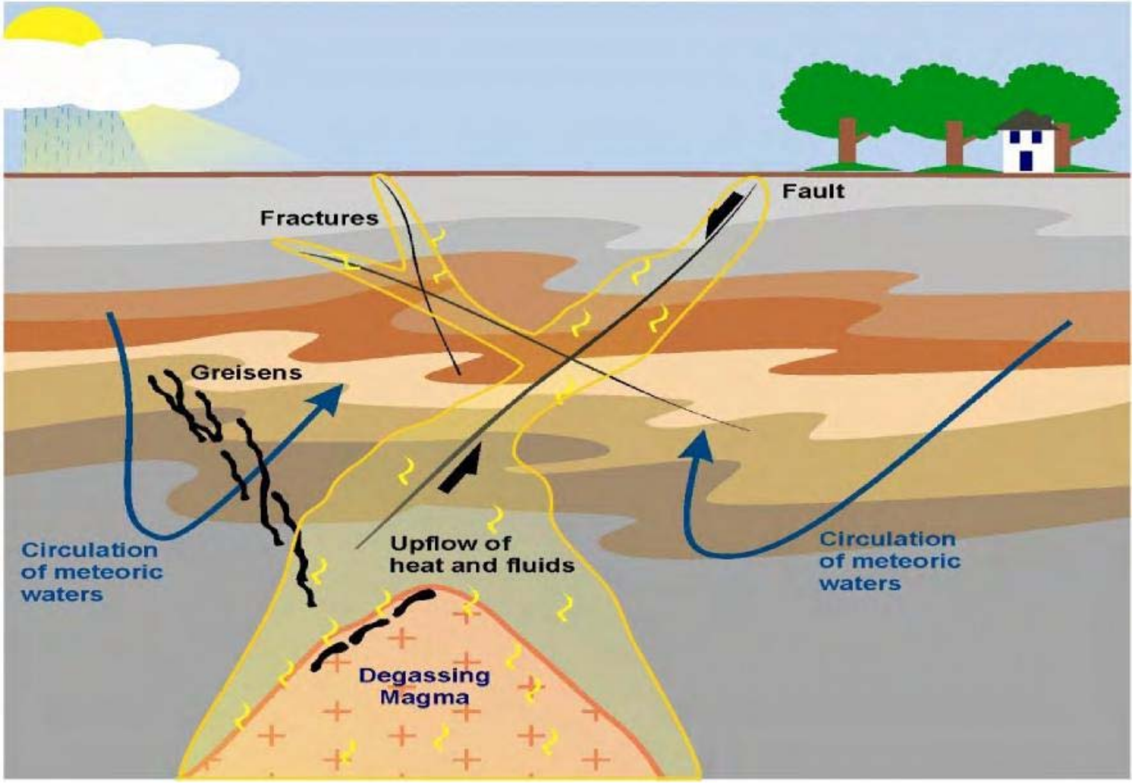


Figure 8. Conceptual illustration of hydrothermal processes from a granite intrusion that will alter the overlying rocks. After Posiva (2009).

Table 4. Comparison of geological characteristics of sites.

Aspect	Olkiluoto	Forsmark	Implications
Age of main bedrock units	Palaeoproterozoic	Palaeoproterozoic	
Tectonic history of main bedrock units	Similar history with multiple compressive episodes	Similar history with multiple compressive episodes	Polyphase deformation and multiple reactivations of deformation zones at both sites.
Younger rocks formed in extensional settings (rapakivi granites, Cambrian sandstones)	Mesoproterozoic rapakivi granite, olivine diabase intrusions approximately 5 km from site; Satakunta sandstones within 15 km	Late Svecofennian granite intrusions (Singö granite) and Mesoproterozoic Jotnian sandstones gone from vicinity; localized remnants in deepest offshore depressions.	Human-intrusion (mineral resources) scenarios due to these formations or syntectonic hydrothermal systems?
Mafic dykes	Olivine diabase dykes presumably related to nearby intrusions	Gabbro and diorite altered to amphibolites makes up ca 4% of the total rock volume	Lower thermal conductivity (affects canister spacing); possibly significant for hydrogeology if fractured.
Bedrock surface	Corresponds approximately to sub-Cambrian peneplain	Corresponds approximately to sub-Cambrian peneplain	Low topographic relief, also serves as reference surface for evaluating later block movements.
Site boundaries	Regional-scale deformation zones form block boundaries.	Regional-scale deformation zones, anastamosing to enclose a shear lens with pronounced difference in deformation inside vs. outside	These choices facilitate imposition of realistic boundary conditions for models; for Forsmark boundaries also demarcate volume with distinctive structure and fabric.
Dominant rock composition	Substantially (meta)granitic Figure 5	Granitic to granodioritic Figure 5	Similar bedrock chemistry
Dominant rock fabric	Migmatitic gneiss	Foliated granite-granodiorite	Rock fabric influences thermomechanical properties including fracturing
Minor rock types of note		"Vuggy" granite produced by localized quartz dissolution	Depending on extent, may provide additional high-conductivity flow paths beyond those represented in hydrogeological model. Thermomechanical properties not known.
Fracture intensity (open fractures)	Approximately 3–4 per m at 50–100 m depth, generally in range 1.5 to 2.5 per m at depths below 150 m (Hartley et al., 2009, Figure 5-9, p. 32).	1.05 per m in fracture domain FFM01 for depths of less than 400 m, and 0.54 per m at greater depth (sums of Terzaghi-corrected linear fracture frequencies for all boreholes over all fracture sets, based on data in SKB, 2008, Tables 8-3 & 8-4, p 251).	Larger volumes of very low-permeability fractures can be expected for the target volume at Forsmark.
Dominant fracture sets	Three main fracture sets by orientation, Nominally horizontal set much stronger; nominally vertical sets striking in N-S and E-W directions.	Three main fracture sets by orientation, Nominally horizontal set much stronger; nominally vertical sets rotated approximately 45° relative to N-S and E-W.	Stronger horizontal vs. vertical brittle structure anisotropy expected at Olkiluoto; expected principal directions of effective permeability tensors align with chosen model grids at both sites.
Fractal scaling (clustering) of fractures	At least one of two outcrops analysed appears to be weakly fractal; both outcrops show significant deviations from a Poisson model (Buoro et al., 2009).	Outcrop analysis indicates weakly fractal clustering of fractures.	Enhanced connectivity of fracture networks, relative to what is expected from simple Poisson-process DFN models (such as have been used in hydrogeological models of both sites).
Correlation of rock-mass fractures to brittle deformation zones	Fractures interpreted as belonging to the "damage zone" or zone of influence for each brittle deformation zone have been included in the deformation zones rather than the rock mass. Residual correlations not analyzed.	Methodology for assigning fractures to deformation zones vs. rock mass similar to Olkiluoto. Strong, statistically-significant residual differences were found between fractures in rock mass "affected by deformation zones" vs. remaining rock mass (Fox et al., 2007).	A correlation could increase the likelihood of strong hydraulic connections between fractures that intersect deposition holes and nearby deformation zones.
Fracture size distribution	Uncertainty high for larger fractures (>5 m scale) due to limited surface exposure and mapping scale in tunnels. Alternative size distributions (lognormal vs. power-law) used to test consequences.	Uncertainty high for larger fractures (>5 m scale) due to limited surface exposure. Alternative power-law distribution parameters used to test consequences.	Affects fracture network connectivity; range of possibilities has not necessarily been bounded by the alternative models tested.

the formation of finely disseminated hematite, the alteration involved ‘saussuritization’ (conversion of Ca-rich to Na-rich plagioclase and formation of epidote and calcite) and conversion of biotite to chlorite. A localised alteration process has affected granitic rocks in the north-eastern part of the area, whereby ‘albitization’ has involved replacement of K-feldspar by an albite-rich plagioclase and quartz. Unlike the red-staining hematite alteration, albitization is not related directly to fracturing but rather to amphibolite occurrence in dykes.

A third type of alteration at Forsmark has been the formation of “vuggy granite” by the dissolution of quartz. Most occurrences of vuggy rock occur inside or close to fracture zones and are typically seen in drillcore for intervals of at least several metres borehole length. In one place, a vuggy zone links two gently dipping fracture zones and thus has at least local hydraulic significance. The scale, spatial pattern, and potential impact of vuggy granite as a path for radionuclide transport is an unresolved issue in the Forsmark site investigations.

4 Hydrogeological properties

4.1 Regional setting

Olkiluoto is on an approximately 10 km² coastal island in the Baltic, separated from the mainland by a narrow strait. It is thus surrounded by water at sea level, limiting the possibility for regional groundwater flow to influence the site. Present-day groundwater flow is expected to be driven mainly by local topography on the island, in combination with density contrasts due to brackish and saline waters that have not reached equilibrium (due to the very slow rate at which diffusion equilibrates between saline and fresh waters in the pore space, combined with ongoing rapid land rise).

With continued land rise relative to sea level (currently at a rate of 6 mm/yr, primarily due to post-glacial isostatic rebound), Olkiluoto will eventually connect to the mainland. Within 2000 years, the sea could be as much as 2 km distant from the site, and regional groundwater flow could be a more significant component of flow at the site.

Forsmark is also presently a coastal site, with the Baltic bordering the site to the NE, and with a similar rate of land rise relative to sea level. Unlike Olkiluoto, the proposed repository site is already connected to the mainland. However, the site contains a string of lakes and low wet areas running from NW to SE, which are still less than a meter above sea level. Some of these lakes show evidence of seawater inflow during storm surges. Thus groundwater levels are still strongly influenced by the Baltic. Regional flows from higher-elevation areas inland (as high as 20 m.a.s.l. within 2 km) could discharge within the site as a consequence of this coastal setting.

As for Olkiluoto, the coastline at Forsmark will continue to recede seaward with continuing land rise due to postglacial isostatic rebound. Thus, the regional hydrological setting of the two sites will become more similar as the current interglacial period continues.

The climate of the two sites is similar (humid continental with mild summer and cool winter, with local marine influence), as they are only about 200 km apart across the Gulf of Bothnia, and are separated by less than a degree of latitude. At both sites, recharge to the deep bedrock appears to be limited by hydraulic conductivity rather than precipitation, so the minor differences in precipitation are unlikely to significantly affect deep groundwater flow.

4.2 Surficial hydrology

Both sites have low relief, due to a history of peneplanation and later continental glaciation. Olkiluoto has an average height of 5 m above sea level; with a maximum elevation of 18 m. Local topographic gradients are on the order of 1% or less. The topography at Forsmark is even more subdued, with maximum elevations under 10 m.

At both sites, the bedrock is poorly exposed due to Quaternary deposits, mainly glacial till. Typically the deepest layers of till are found in bedrock surface depressions. The tills at Olkiluoto are on average coarser, with more sand versus more clay at Forsmark, and thus can be expected to be more permeable on average. Forsmark also contains organic gyttja deposits, particularly in the bottoms of lakes and fens, which further reduce the vertical permeability of near-surface sediments.

Surface hydrologic features at both sites consist of small streams, fens, and natural lakes (at Forsmark) or artificial reservoirs (at Olkiluoto). The lakes at Forsmark are underlain by clays and gyttja which impede hydraulic communication between lakes and bedrock. The Korvensuo reservoir on Olkiluoto presumably has less of such deposits, and is interpreted as a source of infiltration estimated as 21–24 m³ per day (Posiva, 2009, p. 69).

Water balance calculations (Karvonen, 2008; Johansson, 2008) indicate that runoff is modest at both sites: about 175 mm/a or 32% of annual precipitation at Olkiluoto, versus about 155 mm/a or 28% of annual precipitation at Forsmark. Evapotranspiration accounts for 310 mm/a at Olkiluoto vs. 400–410 mm/a at Forsmark. Estimates of recharge from Quaternary deposits into the less permeable bedrock are very similar (10 mm/a for Olkiluoto vs. 11 mm/a for Forsmark). For Forsmark, the net downward flow in the bedrock is however estimated to be only 2–3 mm/a, due to localized discharge within the site.

Both sites contain, or closely border, underground facilities which act as sinks for groundwater. The ONKALO tunnel at Olkiluoto is within the site and is planned to function as part of the proposed disposal facility, and the VLJ (a low- and intermediate-level radioactive waste facility) is on the western part of the island. The SFR (another low- and intermediate-level waste facility) adjoins the Forsmark site but lies beyond a major regional deformation zone (the Singö Zone), which is interpreted as a hydrogeologic barrier, and thus limits the hydrologic impact within the site.

4.3 Bedrock permeability

At both sites, the principal information regarding permeability of typical bedrock (“rock mass”) comes from hydraulic injection tests in 5 m to 20 m sections of drillholes, and differential flow-logging using the Posiva Flow Log (PFL). Larger-scale hydrologic testing using interference tests in multiple drillholes has focused on the more permeable deformation zones, which are discussed separately below. The single-hole methods essentially measure the local transmissivity of fractures at their intersections with the drillholes. Injection tests sample all conductive fractures. The PFL detects only those that participate in large-scale flow networks.

The uppermost 150 m of the bedrock at Forsmark is recognized for having extensive horizontal fractures or sheet joints, which produce very high yields in shallow boreholes (median value of 12,000 liters per hour in the first 22 percussion-drilled boreholes, about 20 times the median yield of domestic water wells in nearby areas outside of the candidate area). This part of the bedrock has nearly uniform groundwater levels close to 0.5 m.a.s.l., and showed extensive and rapid transmission of drawdowns during a large-scale pumping test. For these reasons, the uppermost 150 m of the bedrock within the candidate area is treated as a “shallow bedrock aquifer” in SDM-Site. This “shallow bedrock aquifer” may have a safety function, by short-circuiting the effects of local topography as driving forces for groundwater flows at proposed repository depths.

At Olkiluoto, the hydrogeologic properties of the shallow bedrock are less well characterized, due to fewer “B” holes (short, core-drilled holes to cover the upper 100 m of the rock which is cased in the telescopic drilling method that was used for the deeper drillholes at both sites). The mean water table at Olkiluoto shows substantial effects of local topography, suggesting that the uppermost bedrock at Olkiluoto is not so highly permeable as the corresponding bedrock at Forsmark.

In the target volumes at proposed repository depths, the bedrock at both sites is less permeable, with relatively few water-conducting fractures. Both of these sites can be considered to be “tight” rock at these depths, but the Forsmark site appears to be extraordinarily tight, with only about one PFL anomaly per 250 m of borehole in rock mass within the target volume (vs. one per 50 m at Olkiluoto). However, the existence of connected flow paths in such sparsely fractured rock is noteworthy as a constraint on hydrogeological conceptual models.

Upscaling from these single-hole measurements, to effective permeabilities or hydraulic conductivities on the scales of blocks for calculations in hydrogeological models (typically 50 m) is dependent on the conceptual model used. For both sites, the primary interpretation is based on a stochastic discrete-fracture network (DFN) conceptual model, as was discussed in terms of general geology in Section 3.4, and is discussed further in terms of hydrogeology below.

Effective rock-mass permeabilities have also been estimated by calibration of continuum (equivalent porous medium, or EPM) models to hydraulic measurements. However, such calibrations are mainly sensitive to the hydrogeological zone permeabilities, and less sensitive to rock mass properties at both sites.

For Olkiluoto, the effective hydraulic conductivity is predicted to be anisotropic, with horizontal conductivity exceeding vertical conductivity by a median factor of 2 to 3, for all model variants and depth zones (Hartley *et al.*, 2009, p. 83). Effective block scale permeabilities for the hydrogeological DFN model used in SDM-Site Forsmark have not been presented in the same way as for Olkiluoto.

From comparing figures presented by Follin *et al.* (2007), it appears that upscaled hydraulic conductivities for the bedrock at proposed repository depths, as predicted by the respective hydro-DFN models, are somewhat lower (by roughly an order of magnitude) for Forsmark than for Olkiluoto. It should be kept in mind that this is a comparison of model predictions based on DFN models which have many uncertainties, rather than a direct comparison of measurements.

4.4 Deterministic hydrogeological zones

Both sites have been characterized in terms of hydrogeological zones which are based on the geological interpretation of brittle deformation zones.

The Forsmark brittle deformation model has been developed starting with a larger-scale (11 km × 15 km) lineament analysis that included detailed seabed bathymetry of the offshore portion of the area. At Olkiluoto, lineament analysis has been performed on similar scales (Paananen and Kuivamäki, 2007) but in OSD 2008, deformation zone are delineated only on the island and around its edges. The inclusion of more structures based on bathymetric lineaments at Forsmark may provide more realistic connectivity of the site-scale hydrogeological model to the far-field boundary conditions.

Gently- to moderately-dipping brittle deformation zones are important for the hydrogeological models of both sites.

At Forsmark, the deformation zones which are interpreted as being most significant for site-scale flow (other than the regional shear zones that bound the shear lens that contains the candidate site) are a stack of gently dipping brittle deformation zones that dip SE or SSE. The target volume for the proposed repository is in the footwall of one of these, Zone A2. These gently dipping zones show only brittle deformation. Most exhibit evidence of reverse dip slip and subordinate strike-slip displacements, implying origins in a compressive tectonic environment as thrust faults, but they also

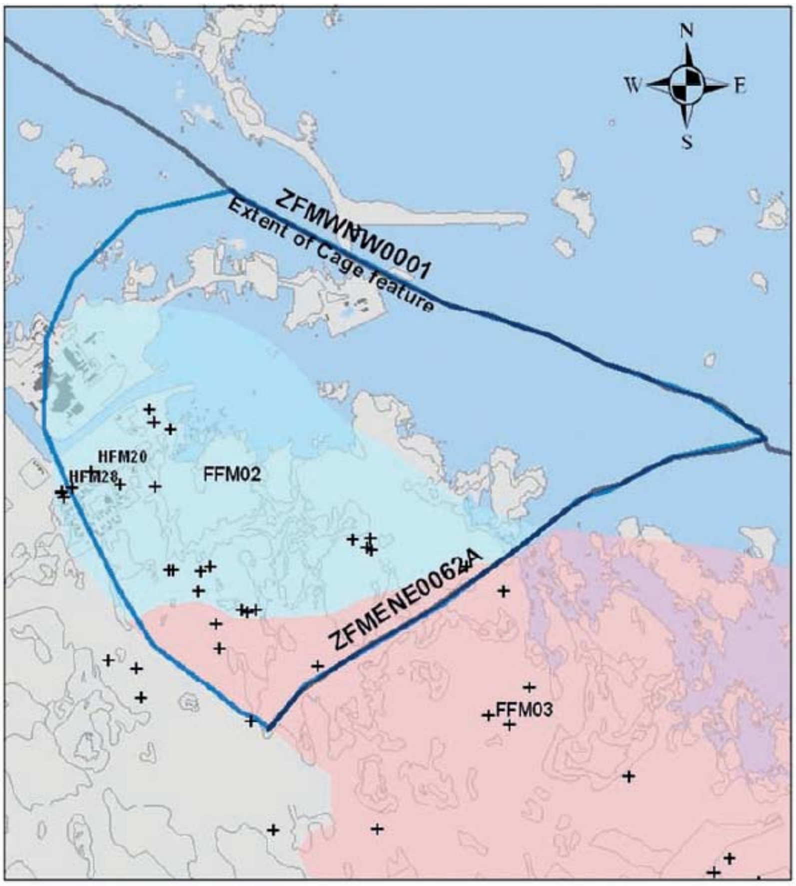


Figure 9. Interpreted extent of the shallow-bedrock aquifer formed by extensive sub-horizontal sheet joints at Forsmark. From SKB (2008, Figure 8-26).

are interpreted as having been reactivated multiple times. Hydrologically these zones indicate strong, laterally extensive connections across the site. This has been confirmed by responses in observation wells during in pumping tests.

Olkiluoto similarly has a system of brittle deformation zones that dip moderately toward the SE. These zones account for the majority of the transmissive fractures that have been found in drillholes at proposed repository depths. However, highly transmissive fractures appear to be heterogeneously rather than uniformly distributed throughout these deformation zones. The lateral limits of these zones are justified in part by observations of high drawdowns in pumping tests.

The local-scale hydrostructural model for Forsmark includes several dozen vertical/subvertical hydrogeological zones, while the model for Olkiluoto includes just one. These additional vertical/subvertical hydrogeological zones at Forsmark result in a much more interconnected network of hydrogeological zones, particularly in the vertical direction, via which groundwater can circulate. In contrast, at Olkiluoto such circulation would need to be partly through the lower-conductivity rock mass.

One question is whether the Olkiluoto site truly contains much fewer vertical/subvertical brittle deformation zones, or if these simply could not be distinguished from the rock mass. At Forsmark, the vertical/subvertical zones tend to be relatively narrow features rather than broad zones, and in places may be represented by just a few discrete fractures. The higher hydraulic conductivity of the rock mass at Olkiluoto could conceivably be due to inclusion of more such features in the stochastic part of the model. However, as discussed above, the rock mass at Olkiluoto is also evaluated as being anisotropic with higher conductivity in the horizontal direction than vertically. This, in combination with the dearth of vertical deterministic hydrogeological zones, means a site-scale fabric that strongly favors horizontal rather than vertical flow.

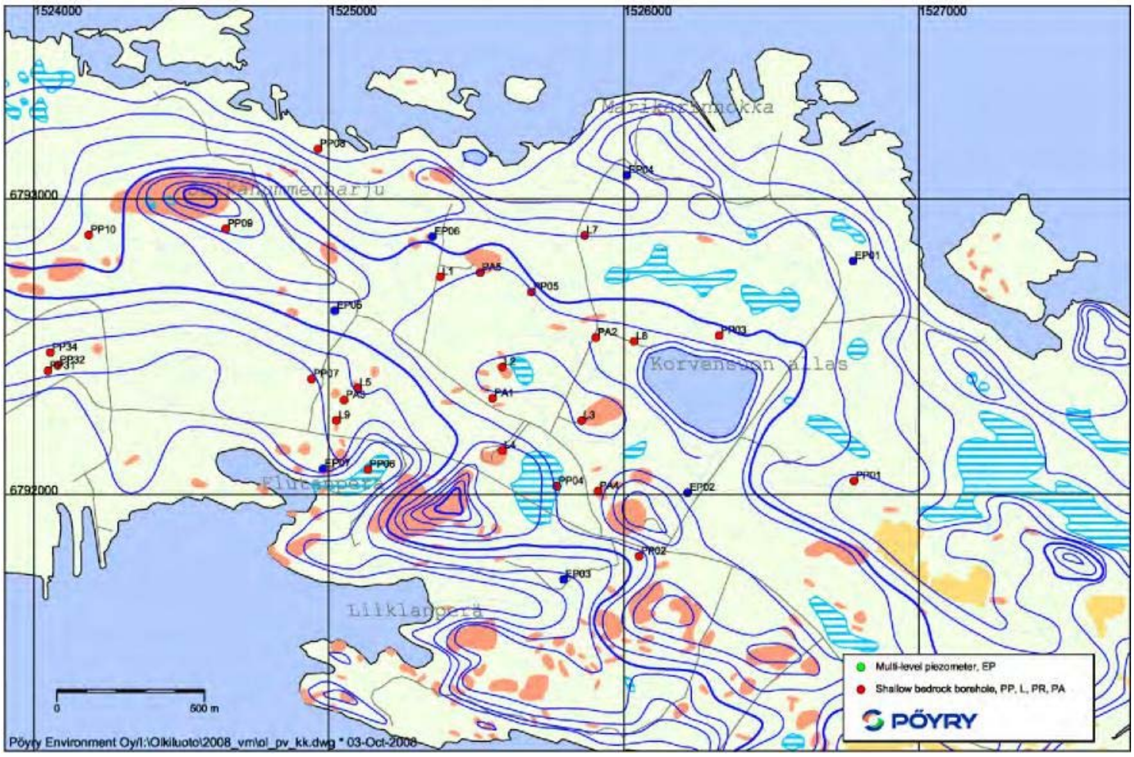


Figure 10. The mean groundwater table at Olkiluoto. After Posiva, 2009.

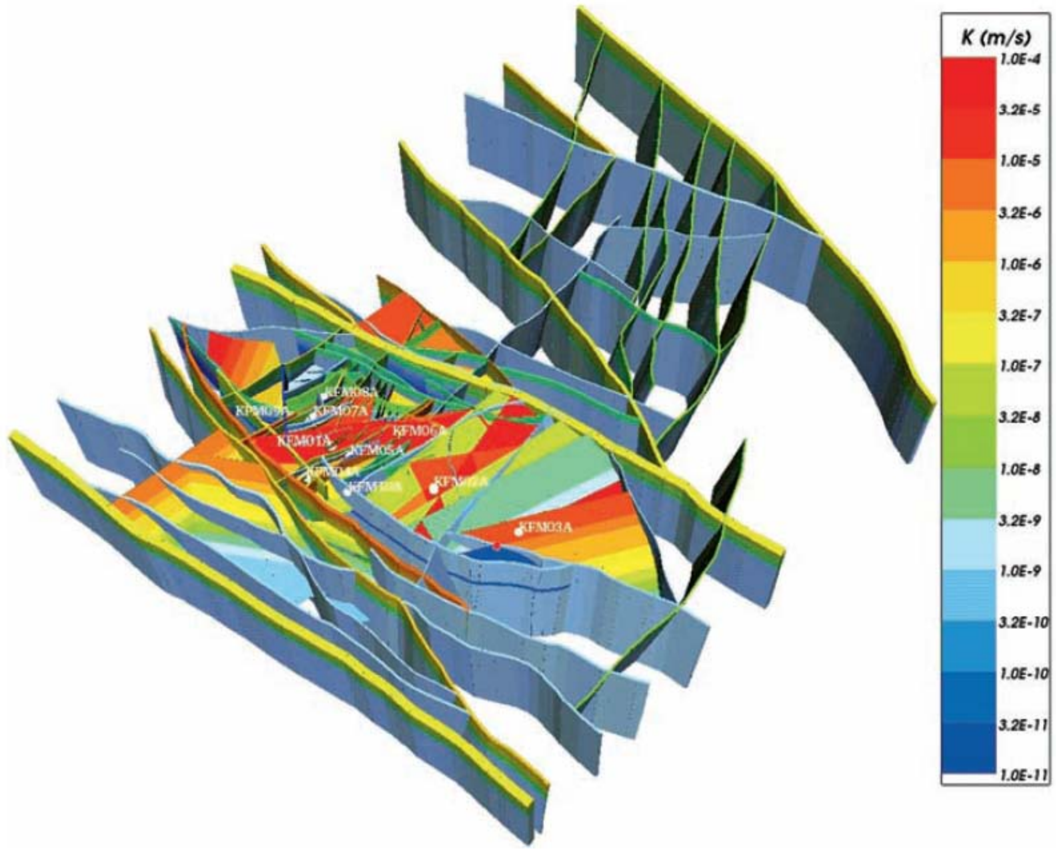


Figure 11. Deterministic hydrogeological deformation zones at Forsmark site, viewed from above. The thicknesses in the figure are equal to the interpreted hydraulic widths of the zones; the color scale indicates the depth-dependent hydraulic conductivity is shown. The shallow dipping zones in the tectonic lens are the most transmissive. From SKB (2008, Figure 8-29).

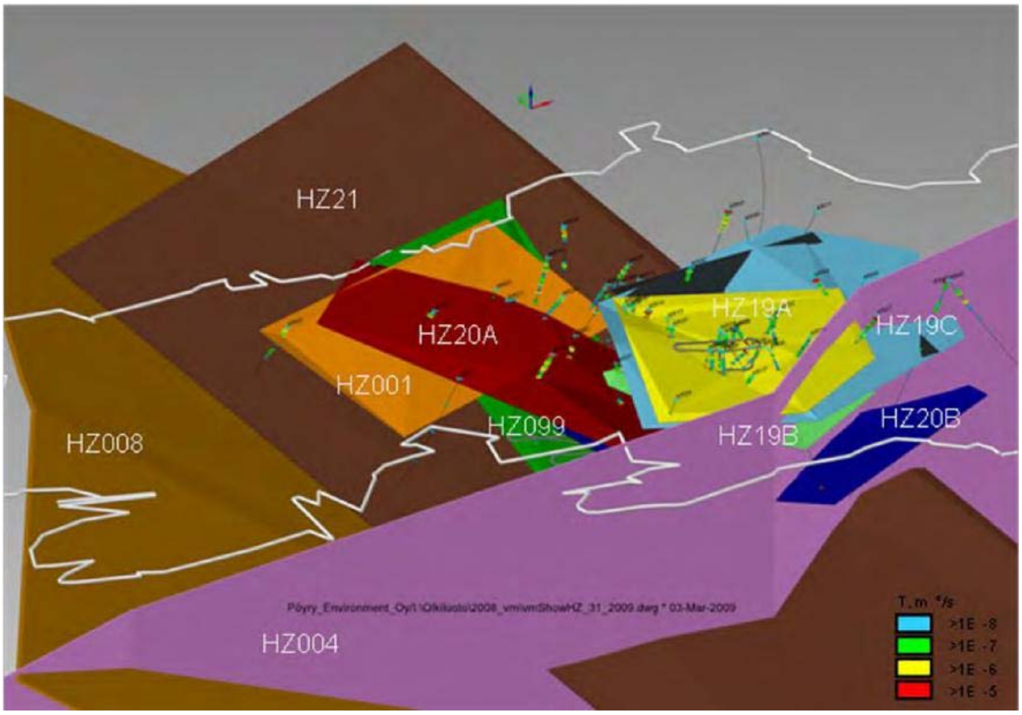


Figure 12. Deterministic hydrogeological zones in Olkiluoto, view towards northeast. The transmissivity of the zones is shown in four different classes: blue T>1E-8, green T >1E-7, yellow T >1E-6 and red T >1E-5 m/s. (From Posiva, 2009, OSD-2008, Figure 6-2).

4.5 Stochastic features

For both sites, hydrological discrete-fracture network (Hydro-DFN) models are developed to model the fractures in the bedrock outside of the identified brittle deformation zones, in terms of their contribution to bedrock permeability and connectivity. The Hydro-DFN models are defined in terms of probability distributions for the same geometric properties as used to define the Geo-DFN models (as discussed in Section 3.4), plus probability distributions or correlation relationships for fracture transmissivity. A combination of empirical and theoretical relationships between fracture transmissivity and aperture are used to develop estimates of porosity and flow-wetted surface (either a cubic-root relationship which is based on a theoretical relationship for flow in parallel-plate fractures, with an empirical scaling factor, or a square-root relationship which is entirely empirical).

From the dominant orientations of the fracture sets in the Geo-DFN models (as discussed in Section 3.4), it might be expected that the principal directions of block-scale hydraulic conductivity tensors will, on average, be aligned with the cardinal directions at Olkiluoto, but rotated about 45 degrees toward the NE at Forsmark. This aligns well with the coordinate systems that have been chosen for hydrogeological modeling at both sites (not a coincidence, since the coordinate systems were chosen in part to align with the larger-scale fabric of these sites).

Conceptual models for fracture location, other than simple Poisson processes, have not been propagated to the hydrogeological models, possibly because of limitations of the software used for Hydro-DFN simulations (which is the same for both sites).

4.6 Understanding of present-day flow situation

The Forsmark and Olkiluoto sites are similar in the general level of understanding of the groundwater flow situation, both in terms of the historical conditions and in terms of the most significant physical processes that govern groundwater flow and its evolution.

Both sites are in similar climates (so have similar precipitation and evapotranspiration regimes). Both are coastal sites with low relief which have emerged from below the Baltic within the past 3000–2500 years, and are still just a few meters above sea level on average. They share similar histories of Weichselian glaciation followed by deglaciation ca. 11,000 y ago. It is inferred that glacial meltwater infiltrated the bedrock as the ice margin retreated. In the waning stages of deglaciation, both sites were submerged below the mildly saline Yoldia Sea, then the glacial lake Ancylus. The saline Littorina Sea covered Olkiluoto from 8000–4500 y ago reaching maximum salinity of about 10‰ (about 5600 mg/L Cl^-), after which the brackish conditions of the present-day Baltic were established. A slightly different interpretation of the Littorina stage has been reported for Forsmark, starting at 9500 y ago and reaching a maximum salinity of about 15‰ (about 8400 mg/L Cl^-) at about 6500–5000 y ago. These may be real differences for example due to geographic and topographic positions of the sites or they may simply be artifacts of different interpretation teams. Thus the hydrologic boundary conditions over the past 15,000 years or more have been broadly similar.

These past conditions influence present-day groundwater flow, primarily in terms of how they influenced the salinity and hence density of waters that remain in the bedrock. Both sites also have much older, deep “shield brines” of higher salinity and density (note: they are nominally ‘brines’, but not necessarily at brine level of salinity) than groundwaters at proposed repository depths. The denser relict waters impede circulation of less dense meteoric waters to repository depths. Mixing between these waters can occur by advective dispersion in the most transmissive fractures and deformation zones, a relatively rapid process. However in the less conductive portions of the bedrock, mixing is governed mainly by diffusion which requires very long time scales for equilibration. At both sites, groundwater models (as presented by SKB, 2008 and Posiva, 2009) and geochemical data (as discussed in Section 5 of this report) indicate a disequilibrium between the relatively mobile water in the most transmissive fractures and deformation zones, versus less mobile water in tighter portions of the bedrock. Further details of pore water hydrochemistry at the two sites can be found in Section 5.6.

Groundwater flow models of both sites have been calibrated with respect to observed salinities (TDS) in drillholes (Figure 13). The resulting models show some agreement in terms of general trends with depth, but also many differences. For example, at Forsmark (SKB, 2008 p. 273) a transition to high salinity in excess of Littorina salinity is predicted just below 600 m depth in drillhole KFM03A, but this is not seen in the data until the depth interval 800–900 m; an interval of low-salinity water (with a pronounced density inversion compared to shallower depths) is predicted for depths from about 230 m to 400 m in KFM01D, but the data show a rather steady increase with depth through this interval. For Olkiluoto (Posiva, 2009 p. 267), the most recent model predicts an abrupt transition to TDS of about 7.5 g/L just below 150 m depth in drillhole KR5, but data show that this transition takes place between 50 m and 100 m depth; conversely, a transition to this salinity level in KR3 predicted for 150 m depth is observed around 400 m depth.

These difficulties in predicting transitions in salinities are understandable. The differences between models and observation, in terms of where the interfaces between waters of different salinities are found, are functions both of site properties that govern advection through the more transmissive features (e.g. fracture zone transmissivities, extents, and connectivity) and site properties that govern diffusive exchange (effective block sizes for low-permeability rock bounded by flowing fractures, and effective diffusivities in these less permeable blocks, which in turn depends on the connectivity characteristics of networks of smaller and less transmissive fractures). All of these site properties can reasonably be expected to be heterogeneous, resulting in patterns that are difficult to predict using models in which some of these parameters are treated as homogeneous, and where the spatial pattern of variation of other parameters is not well characterized.

Considering these factors, the differences of up to several hundred meters' depth that are seen for transitions predicted by the groundwater flow models, versus the locations of those transition as shown by data, do not necessarily indicate a poor understanding of the main processes or general patterns for these sites. However, they suggest a need for caution in applying some of the key predictions of these models, for example, regarding the depths to which groundwater recharge-discharge cells are driven by topography, and moderated by saline waters at depth.

For both sites, diffusive exchange rates between pore waters in the relatively immobile matrix of the rock mass and more mobile water appear to be a key uncertainty for modeling the long-term evolution of groundwater. At both sites, these rates are constrained only by calibration of large-scale models

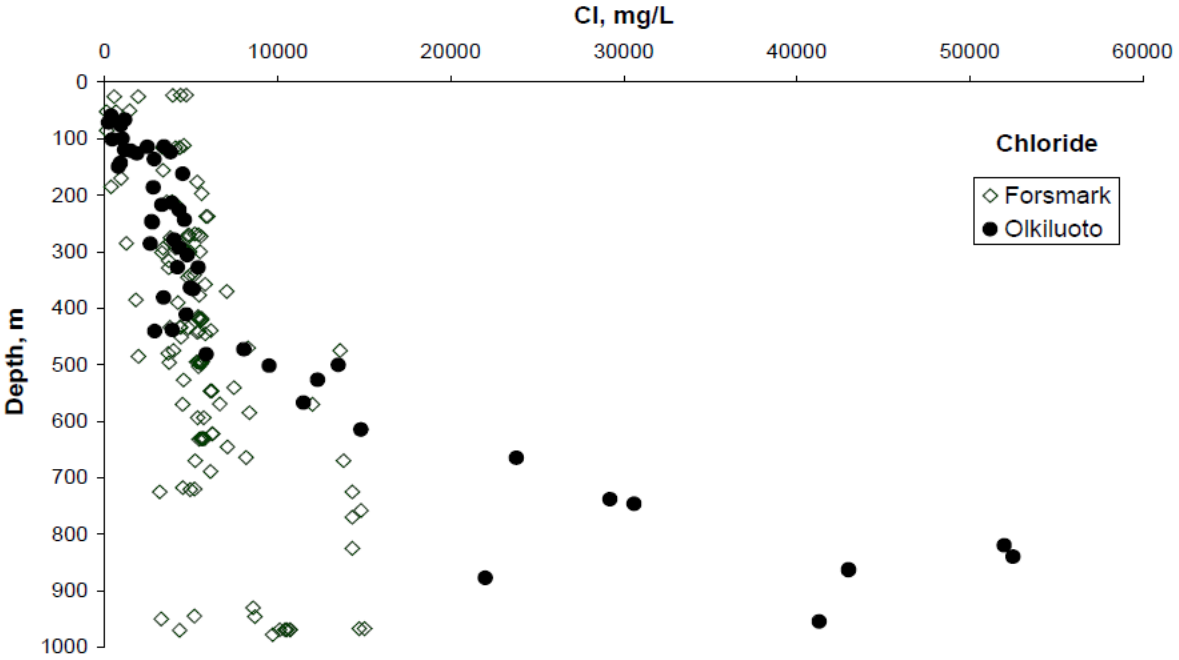


Figure 13. Depth profiles of chloride concentrations at Olkiluoto and Forsmark, illustrating the much steeper salinity gradient below about 600 m depth at Olkiluoto.

Table 5. Comparison of hydrogeological characteristics of sites.

Property	Olkiluoto	Forsmark	Implications
Setting	Coastal island site with low topographic gradients and strong influence of Baltic	Coastal mainland site with low topographic gradients and strong influence of Baltic	Slight difference in position relative to coastline, but significance will decrease with ongoing shoreline recession.
Climate	Humid continental with marine influence	Humid continental with marine influence	
Quaternary cover	Mainly glacial till, silty to sandy (more permeable), typically 2–5 meters deep but up to 14 m deep.	Mainly glacial till, silty to clayey (less permeable), up to 15 m deep.	
Surface water bodies (in addition to Baltic)	Korvensuo Reservoir (approx. 10 ha), plus mires and other wetlands, ditches; reservoir interpreted as source of infiltration	Two natural lakes (Bolundsfjärden and Fiskarfjärden) which cover close to 50 ha each, plus numerous smaller lakes, mires, and other wetlands; lakes underlain by clay which impedes hydraulic communication with bedrock	
Precipitation (long-term average)	550 mm/a	563 mm/a	
Evapotranspiration	310 mm/a	400-410 mm/a	
Runoff	175 mm/a	150-160 mm/a	
Recharge to bedrock	10 mm/a	11 mm/a	May not reflect actual rate of recharge to deep bedrock due to local recharge-discharge cells.
Shallow bedrock	Less well characterized due to limited number of drillholes with upper 150 m uncased; calibrated value of hydraulic conductivity is 10^{-7} m/s (Table 6-2 of R-2009-01, p. 258).	Highly transmissive; typical hydraulic conductivity values on the order of 10^{-5} m/s. Treated as "shallow bedrock aquifer"	Local topography may have a stronger influence on groundwater flow patterns at proposed repository depths, at Olkiluoto compared to Forsmark.
Relation of water table to bedrock surface	Strong correlation of water table to topography within site (R 2009-01, p. 221).	Water table is nearly flat within site, generally less than 0.5 m.a.s.l., with only weak correlation to bedrock surface topography.	Supports estimates of higher hydraulic conductivity in shallow bedrock at Forsmark vs. Olkiluoto.
Frequency of PFL water-conducting fractures at proposed repository depths	About 1 per 50 m	About 1 per 250 m	Tight rock with widely spaced flowing networks at both sites, even more so at Forsmark.
Block-scale hydraulic conductivities at proposed repository depths based on Hydro-DFN model	Effective hydraulic conductivities for a 50 m block scale have a logarithmic mean value in the range 2.4×10^{-11} m/s to 3.5×10^{-10} m/s, with a standard deviation of 0.7 to 1.2 orders of magnitude, depending on fracture size and transmissivity distributions.	Block-scale effective hydraulic conductivities not explicitly presented; plots (Follin et al., 2007) indicate that values for the rock mass at 450 m depth are nearly all in the range 10^{-12} m/s to 10^{-9} m/s, and mainly below 10^{-11} m/s.	About one order of magnitude higher at Olkiluoto than at Forsmark
Anisotropy of rock-mass hydraulic conductivity	Horizontal hydraulic conductivity inferred to be 2–3 times higher than vertical hydraulic conductivity.	No clear indication of rock mass anisotropy	Combined with the dearth of steeply dipping hydrogeological zones, this results in a site-scale fabric at Olkiluoto that is relatively resistant to vertical movement of groundwater.
Gently dipping brittle deformation zones	Gently SE dipping brittle deformation zones (thrust-faulting origin but reactivated) are important to the hydrogeological models.	Gently SE dipping brittle deformation zones (thrust-faulting origin but reactivated) are important to the hydrogeological models.	Zones above the proposed repository may partly shield repository from deep circulation due to local topography, but deeper zones could potentially carry elevated pressures to base of model.
Steeply dipping brittle deformation zones	One	Over 30	These provide vertical connectivity for the Forsmark hydrogeological model.
Underground openings at/near site	VLJ low- and intermediate-level waste facility on west part of island; ONKALO ramp under construction	SFR low- and intermediate-level waste facility on north side of Singö zone	Act as sinks for present-day groundwater flow.

Property	**Olkiluoto**	**Forsmark**	**Implications**
Connectivity to boundary conditions	Sparsely connected due to very few interpreted lineaments and hydrogeologic zones in areas currently covered by the sea.	Less sparsely connected, although density of interpreted lineaments and hydrogeologic zones is noticeably lower for undersea areas than on land.	Regional flow component in site-scale hydrogeological models could be underestimated.
Quaternary history, especially in most recent glaciation cycle		Minor differences in timing and duration of ice cover, and timing of transitions to subaqueous and subaerial conditions	Surface boundary conditions (hydrogeological, hydrogeochemical, mechanical, and thermal) for past 12,000 years generally similar at both sites.

to a sparse set of groundwater samples from depth. The effective parameters for these long-term diffusion processes represent diffusion between a flowing fracture network and a much less conductive rock mass on scales of meters, and thus likely differ from effective parameters for radionuclide retardation processes which act on a scale of centimeters in microfracture networks rather than megascopic fracture networks.

5 Hydrogeochemical properties

The comparisons and discussions in this section are primarily concerned with the hydrochemistry of ‘deep’ groundwaters at each site that occur at >100 m depth. Data and conceptual process interpretations to characterize the surface water and shallow groundwater have been derived from numerous samplings at Olkiluoto and Forsmark and are reported by Posiva and SKB. The hydrochemical SDMs for shallow (<100 m) groundwaters have been developed and reported separately from the models for the deeper groundwater system.

Although the existing shallow SFR facility at Forsmark is within the local model area, no hydrogeochemical data from boreholes and underground monitoring points at SFR have contributed to the development of the hydrogeochemical SDM for the proposed deep spent fuel repository location.

5.1 Water sampling and hydrochemical measurements in deep boreholes

Most or all of the drillholes at Olkiluoto have been sampled, soon after drilling, at one or more depth intervals using pumped extraction with a double-packer downhole tool. The downhole PAVE tool consists of a membrane pump operated from the surface and one or more sample vessels with an internal gas-driven piston that compensates for pressure changes and preserves water samples at *in-situ* pressure. Subsequently many of the boreholes have been re-sampled after the installation of multi-packer systems, however many of the boreholes were left open for long periods (*i.e.* several years) prior to multi-packer installations so these water samples may not be representative due to cross-flow within drillholes.

Efforts aimed specifically at sampling fracture groundwaters in rock domains with lower transmissivity at Olkiluoto have not revealed any substantial contrast with groundwaters in more transmissive domains, though slightly higher Cl^- concentrations and lower HCO_3^- presumably reflect the tendency for less mixing of dilute meteoric water in the former. Groundwater samples collected from the hydrogeological zones HZ19A and HZ20A in the immediate vicinity of the ONKALO have compositions that are slightly dilute compared with earlier groundwater samples taken at comparable depths in surface-based boreholes (Penttinen et al, 2011, pp 98 & 110). This can be interpreted as evidence that there has been some drawdown of shallow dilute water towards the ONKALO excavation, though there is also evidence of a more general pattern of slightly greater infiltration of fresh waters in the hydrogeological zones.

Water samples have also been collected from 2005 onwards from ‘groundwater stations’ (PVA 1 to 6) and from 2004 onwards in pilot holes (PH 2 to 6, 8 to 11) in the ONKALO access tunnel (Posiva, 2009; Penttinen et al, 2011, p 123). These samples have had little significance for baseline hydrochemistry but have been used to search for perturbations due to excavation such as stray materials from blasting, injection and grouting, and also for studies focused on colloids, microbes and organics.

The total number of water samples from drillholes that have been reasonably representative of baseline conditions is 41 (plus another 52 water samples of secondary quality). Another 102 water samples are considered to have some degree of perturbation. Samples have been taken down to about 850 m depth, though most are at ≤ 500 m. The length of sampled intervals has been mostly in the range 2 to 10 m.

Posiva’s PAVE equipment measures pH, Eh and dissolved oxygen (DO) in water pumped from a borehole to a flow-through cell at the surface. pH and Eh data have been obtained for most of the intervals from which water samples have been collected, but a large proportion (perhaps >50%) of these measurements appear to be unrepresentative especially for Eh, and thus also for DO. It is not clear from Posiva's reporting how many measurements are considered to be reliable. A report of PAVE sampling and monitoring of groundwaters from six open boreholes (sampling depths 50 to 867 m) provides data for pH, Eh and DO (Hirvonen and Hatenpää, 2006). A similar data set has been obtained during a long-term pumping test in an open borehole (Paaso et al, 2006). pH values are in the range 7.4 to 8.1, Eh values are in the range -270 to -30 mV, and DO values are consistently below detection limits of the electrochemical probes, *i.e.* either <0.01 or <0.001 mg/L O_2. In several cases (including the two least negative values) the Eh did not stabilize during monitoring, so the overall reliability is not certain though the data tend to indicate reducing conditions as expected.

The same general issues apply also to samples taken for analyses of redox-active solutes, *i.e.* Fe^{2+}, HS^- and probably also CH_4 and H_2. Data for ^{14}C and $\delta^{13}C$ might also have similar uncertainties. Water samples have been collected specially for microbial analyses down to about 450 m depth; about 25 such samples from drillholes have been analyzed.

17 of the drillholes at Forsmark were sampled for hydrochemistry; another 38 boreholes provided water samples to 100–200 m depth (Smellie et al, 2008). 10 of the drillholes were sampled specifically for microbial and gases analyses, and 5 for colloids analyses. Drillholes were sampled using pumping from between double-packer tools at one or more depth intervals, mostly 1–20 m in length although a few intervals were longer. Water samples were collected in downhole sampling vessels (some pressurized) and in some cases also from discharge flow at the surface. Some additional samples have subsequently been collected from multi-level monitoring installations, mostly targeted on a subset of the sampled intervals; these samples tend to confirm the general hydrochemistry measured in the initial samples.

31 water samples with high to moderate quality ratings were obtained from drillholes (plus a further 88 samples of poor quality), and 12 good water samples from boreholes (plus 100 samples of poor quality). The majority of water samples come from above 500 m depth; 11 samples come from 500–1000 m. Samples for colloids, microbes and organics analyses were collected down to 450 m depth, but the technical challenges of sampling from drillholes mean that these samples would have had varying degrees of representativeness. For example, several of the water samples for dissolved gas analyses are known to have been contaminated by nitrogen or argon leaking from the compensating pressure chamber in the special sampling vessel.

pH and Eh data for Forsmark were measured for selected depth intervals using SKB's CHEMMAC downhole monitoring and pumping tool. A rigorous quality control procedure has been used by SKB to identify the most representative measurements, by downhole and/or wellhead monitoring. The resulting data set of representative measurements comprises 17 pH values (down to 1000 m depth) and 9 Eh values (down to 650 m depth except for one at about 940 m). The number of water samples on which reliable analyses of redox-active solutes, Fe^{2+} and HS^-, were obtained is similarly low.

5.2 Salinity (total dissolved solids and ionic strength)

Olkiluoto and Forsmark both have brackish (≤10 g/L TDS) groundwaters down to at least proposed repository depths; these levels of salinity then transition to saline (>10 g/L TDS) waters over differing depth ranges (Figure 13). Salinities reach different maxima at maximum drilled depth, *i.e.* about 1000 m, at the two sites. Olkiluoto generally has brackish groundwater between 30 and 450 m depth, below which observed salinity rises to a maximum of about 84 g/L TDS (about 52000 mg/L Cl^-) at about 1000 m depth (Posiva, 2009, p 314). Forsmark is brackish from about 60 m to 900 m depth in the southern part of the target area and to about 600–700 m in the northern part. The maximum observed salinity below those depths at Forsmark is about 24 g/L TDS (about 15000 mg/L Cl^-) at about 1000 m depth (Smellie et al, 2008).

The distribution of salinity is more spatially heterogeneous at Forsmark than at Olkiluoto (Figure 13); this may relate to the hydrogeological differences: the dominance of large scale vertical conductivity at Forsmark and the dominance of lateral conductivity at Olkiluoto (see Section 4.4). The distinction between the southern and northern parts of the Forsmark siting area reflects the significance of distinct groundwater regimes (footwall and hanging wall domains that are separated by the major sub-horizontal gently dipping deformation zone A2. Although Olkiluoto also has sub-horizontal fracture zones that are known to be major hydrogeological features, *i.e.* to have relatively high transmissivities, they do not seem to cause the salinity heterogeneity seen at Forsmark.

Brackish groundwaters at Olkiluoto are subdivided into brackish-SO_4 waters which have up to 580 mg/L SO_4^{2-} and 5000 mg/L Cl^- generally occurring at 100–300 m depth, and brackish-Cl waters which have <100 mg/L SO_4^{2-} and up to 7000 mg/L Cl^- occurring at 300–450 m (Posiva, 2009). Brackish groundwaters at Forsmark are sub-divided on the basis of Mg^{2+} concentrations into brackish-marine waters (10–250 mg/L Mg^{2+}, at 60–500 m depth) and brackish non-marine waters (10–80 mg/L Mg^{2+}, at >500 m) (Smellie et al, 2008) (Figure 14). Brackish-SO_4 groundwaters at Olkiluoto have 30–250 mg/L Mg^{2+} so are similar to brackish marine waters at Forsmark. Brackish-Cl groundwaters at Olkiluoto have up to 80 mg/L Mg^{2+} so are similar to brackish non-marine waters at Forsmark (Figure 14).

Whilst SO_4^{2-} contents are similar for brackish-SO_4 water at Olkiluoto (up to 580 mg/L) and brackish-marine waters at Forsmark (up to 550 mg/L), they are dissimilar for brackish-Cl water at Olkiluoto (up to 100 mg/L) and brackish non-marine water at Forsmark (up to 200 mg/L).

Several conceptual interpretations arise from these observations:

- Brackish waters with higher SO_4^{2-} contents at both sites are of predominantly Littorina Sea origin.
- During post-glacial Holocene submergence, Littorina water penetrated deeper at Forsmark than at Olkiluoto. This may reflect longer duration of submergence at Forsmark than at Olkiluoto, and/or greater vertical transmissivity at Forsmark than at Olkiluoto, and/or a constraint on deep infiltration due to pre-existing deep groundwater at Olkiluoto being more saline than at Forsmark.
- Sub-horizontal gently-dipping deformation zones and the distribution and frequency of vertical hydrogeological zones are significant at both sites for groundwater movements and mixing, and thus for salinity distributions. The varying salinity distribution at Forsmark indicates that groundwater movement is more restricted down to proposed repository depths in the footwall domain where there are no (or fewer) deformation zones.
- Brackish groundwaters with lower SO_4^{2-} content at both sites are not derived from Littorina but predominantly from dilution of deeper saline waters that are of non-marine origins (based on Mg^{2+} interpretation).

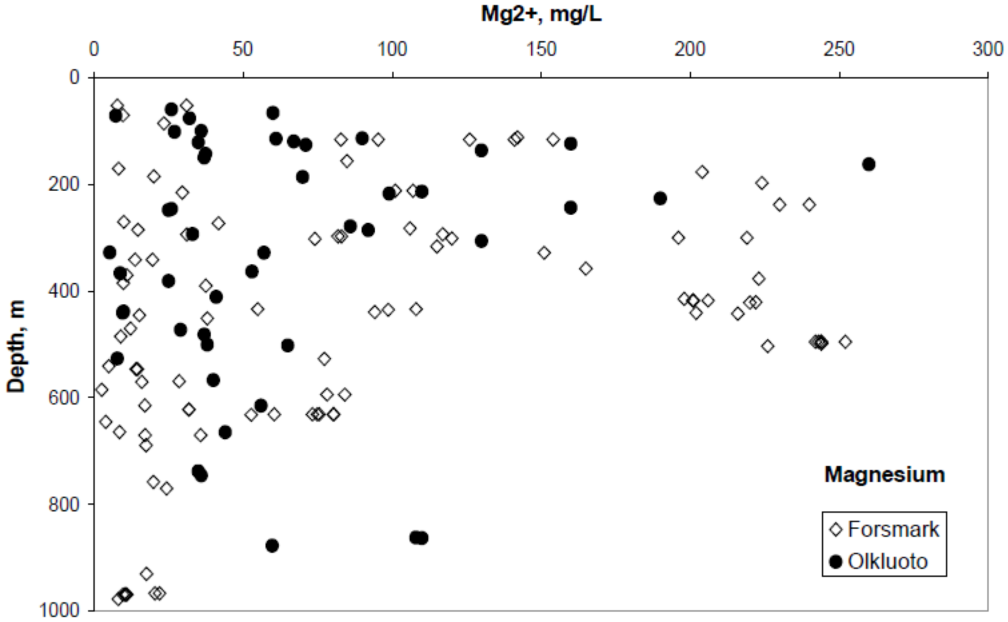


Figure 14. Magnesium concentrations versus depth for Olkiluoto and Forsmark.

- Differences of SO_4^{2-} concentrations in the deeper non-marine brackish waters at Olkiluoto and Forsmark may reflect contrasting sources of SO_4^{2-} in deep saline waters or differing efficiencies of SO_4^{2-} reduction. Posiva infer that the latter is the case and is linked with methane abundance in Olkiluoto groundwaters (see below).

5.3 Redox conditions (dissolved oxygen, Eh, reduced S and N species)

Dissolved oxygen (DO) data obtained by electrochemical probe have not been consistently reported for groundwaters at Olkiluoto and Forsmark. It is understood that this is because of the variable reliability of DO measurements due primarily to the likelihood of contamination by air ingress into the sampling tubing and/or the flow-through cell at the surface. However, as stated above (Section 5.1), 'below detection limit' values of DO, coupled with negative Eh values, have been measured in some groundwaters at Olkiluoto in open borehole conditions. In general, for both sites, DO is inferred to be absent on the basis of Eh values and of iron and sulphur speciation that indicate reducing conditions.

Redox conditions at proposed repository depth ranges are expected to be similar at both sites. For example, the judgment that anaerobic conditions occur at Olkiluoto is supported by Fe^{2+} mostly being in the range 0–1 mg/L below 100 m depth and HS^- mostly being in the range 0–4 mg/L (Posiva, 2009; Penttinen et al, 2011). Reported Eh values for groundwaters at Olkiluoto are scattered with a wide range of +100 to -400 mV, and show no systematic variation with depth. The scatter of values is attributed by Posiva to problems with measurements and this is almost certainly the case. Eh values reported for groundwaters at Forsmark have higher reliability: 13 measurements in brackish and saline groundwaters fall in the range -143 to -281 mV (Laaksoharju et al, 2008). Taking account of pH variations these Eh values for Forsmark are fairly consistent with electrochemical equilibrium for the SO_4^{2-}/HS^- and SO_4^{2-}/FeS_{am} couples and also with Fe^{2+} equilibrium with an iron oxide phase with intermediate crystallinity (cf Banwart, 1999).

The conceptual model proposed for redox at Olkiluoto based on distributions of redox-active solutes has two regimes, above and below a 'metastable interface' at 200–300 m (Posiva, 2009). Above that, SO_4^{2-}/HS^- is suggested as the control whereas below 300 m CH_4/CO_2 is suggested as the control. It is implied that microbially mediated anaerobic oxidation of CH_4 and concurrent reduction of SO_4^{2-} take place in the interface at about 300 m where SO_4^{2-} concentrations decrease sharply with increasing depth and CH_4 concentrations decrease with decreasing depth (Figure 15).

The inferred change of redox-controlling biogeochemistry at Olkiluoto is related to the changing

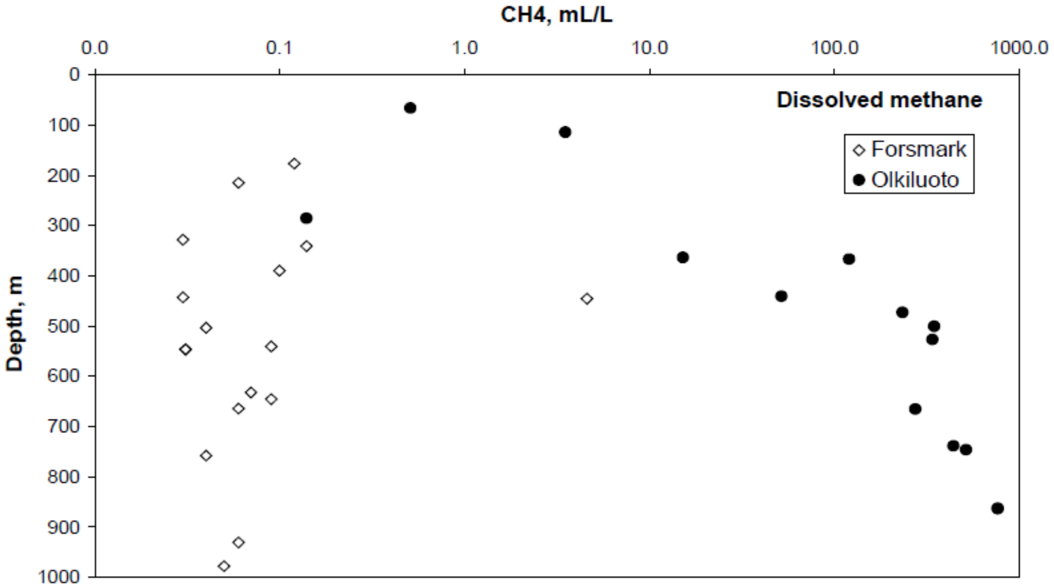


Figure 15. Methane concentrations (plotted on a logarithmic scale) versus depth at Olkiluoto and Forsmark.

Table 6. Comparisons of typical major cation concentrations corresponding to increasing salinities in Olkiluoto and Forsmark groundwaters, based on diagrammatic presentations of data in Posiva, 2009, Pitkänen et al 2003, Penttinen et al 2011 and SKB 2008.

Cl^-, mg/L	Site	Na^+, mg/L	K^+, mg/L	Ca^{2+}, mg/L	Mg^{2+}, mg/L
1000	Olkiluoto	500	5 – 15	150	60
	Forsmark	600	5 – 60	100	30
10000	Olkiluoto	3500	14	3000	65
	Forsmark	2000	10	3500	10
30000	Olkiluoto	8000	20	10000	40
	Forsmark	N/A			
45000	Olkiluoto	9500	29	18000	135
	Forsmark	N/A			

N/A = not applicable because this level of salinity has not been observed at Forsmark.

occurrence of CH_4 which is very low down to 300 m depth below which it increases in brackish-Cl and saline groundwaters to ~1000 mL$_{STP}$ per litre water (Figure 15). Below 300 m depth, HS^- is always <1 mg/L. H_2 concentrations at Olkiluoto increase with increasing depth, from µL/L to mL/L levels. Both CH_4 and H_2 are attributed by Posiva to a dominantly abiogenic source.

CH_4 concentrations at Forsmark are mostly below 0.10 mL/L (Figure 15) whilst corresponding H_2 concentrations are scattered from below detection (around 3 µL/L) up to 370 µL/L.

Data for populations and distributions of microorganisms are similar for the two sites and do not really shed any clear light on variations of biogeochemical processes with depth. Total numbers of cells (TNC) at more than 100 m depth at Olkiluoto are mostly in the range 10^4–10^5 cells/mL (Posiva, 2009) whereas TNC at Forsmark is similar, between 10^4–10^6 cells/mL (Hallbeck and Pedersen, 2008). Most probable numbers (MPN) for various groups of microbes, e.g. sulphate reducing bacteria (SRB), iron and manganese reducing bacteria (IRB and MRB), acetogens, and methanogens, generally do not show clear patterns at Forsmark though they seem to reach maxima at 250–330 m depth at Olkiluoto. These microbial groups are mostly present at all depths at Forsmark though methanogens are very sparse, more so than at Olkiluoto, being detected in only 2 samples. Acetogens are the dominant group at both Olkiluoto and Forsmark, and it is noted that SRB are a low proportion of total microbes. There seems to be a correlation between the MPN for SRB and the value of Eh at Forsmark, adding to evidence for Eh being controlled by the microbially-mediated SO_4/HS redox couple.

5.4 Divalent (Ca^{2+}, Mg^{2+}) and monovalent (Na^+, K^+) cations

The water types at Olkiluoto change with depth from Ca-Na-Mg in fresh groundwaters to Na-(Ca) and Na-dominated in brackish groundwaters. Saline groundwaters change from Na-Ca to Ca-Na types as salinity increases to the maxima seen at Olkiluoto. A similar pattern is seen at Forsmark in the brackish non-marine waters, but the change to Ca-Na types occurs at lower salinities. At both Olkiluoto and Forsmark, Na^+ and Ca^{2+} increase regularly with increasing depth and increasing Cl^-, with the rates of increase changing so that Ca^{2+} predominance takes over from Na^+ predominance in saline groundwaters.

Maximum Na^+ at 1000 m depth is about 10000 mg/L at Olkiluoto and is about 2200 mg/L at Forsmark (with slightly higher Na^+ in more saline groundwaters in the northern part of the target area). Maximum Ca^{2+} at 1000 m depth is about 18000 mg/L at Olkiluoto and is about 4000 mg/L at Forsmark, with higher Ca^{2+} in the northern part of the target area.

Sr^{2+} shows behavior similar to that of Ca^{2+}, with maxima of about 190 mg/L at Olkiluoto and about 70 mg/L at Forsmark.

K^+ concentrations at Olkiluoto are more variable in relation to depth and Cl^- but show a slight increase to a maximum of around 29 mg/L in the deepest samples. K^+ concentrations are variable in brackish marine groundwaters at Forsmark, varying between 5 and 60 mg/L. In contrast to the case at Olkiluoto, maximum K^+ values decrease with increasing depth at Forsmark and are around 10 mg/L at 1000 m.

The patterns of Mg^{2+} variation with depth and in relation to salinity at both Olkiluoto and Forsmark are strongly influenced by the distribution of brackish marine Littorina water, as explained above (Figure 14). Maxima of Mg^{2+} between 250–300 mg/L are seen in the brackish-SO_4 and brackish marine groundwaters at Olkiluoto and Forsmark respectively. In deeper saline waters at Olkiluoto and Forsmark, Mg^{2+} is generally <60 mg/L except in the most saline waters sampled at Olkiluoto in which Mg^{2+} is 100–135 mg/L.

The implications of these differences in cation concentrations and relative proportions, specifically at proposed repository depths, for the geochemical evolution of the bentonite buffer in the engineered barrier systems of proposed repositories at Olkiluoto and Forsmark could be studied by geochemical modelling. Ca:Na ratios are generally higher in groundwaters at proposed repository depth at Forsmark than at Olkiluoto. The hydrogeochemical reasons for these differences, apart from the clear link between Littorina water and Mg^{2+}, are not clear; for example the reasons for different reaction stoichiometries in Ca-Na evolution and for differences in K^+ concentrations are not evident.

5.5 pH, carbonate alkalinity and buffering capacity

Values of pH in groundwaters at Olkiluoto vary between about 7 and 8.2 (Posiva, 2009). In shallow fresh-brackish HCO_3-type waters they are between 7 and 7.5, and then show a tendency to increase to 7.5 and 8.2 in brackish-SO_4 and brackish-Cl waters. In deep saline groundwaters, there is a trend of a slight decrease of pH from around 8 to 7.5 as TDS increases and water composition changes from Na-Ca-Cl to Ca-Na-Cl.

pH in groundwaters at Forsmark varies over similar ranges: 7.3–8.2 in brackish marine waters and 7.0–8.5 in brackish non-marine and saline waters, though there is no clear pattern of variation with depth or salinity in this case (Laaksoharju et al, 2008).

Total alkalinity, predominantly due to dissolved inorganic carbon *i.e.* HCO_3^-, is inversely correlated with salinity at both sites. It is <2 milliequivalents per litre (meq/L) in brackish SO_4 waters at Olkiluoto and <1 meq/L in brackish Cl and saline waters. It is mostly <3 meq/L in brackish marine waters at Forsmark and <1 meq/L in brackish and saline non-marine waters.

In both cases, the main buffering process for pH is interpreted as equilibration with calcite which is almost ubiquitous in fracture-filling mineral assemblages. Studies of fracture minerals at Forsmark indicate that calcite occurs in both the hydrothermal generations and the more recent low temperature generation of fracture minerals. It is one of the most common minerals in open and partly-open transmissive fractures. Similarly, at Olkiluoto, calcite is identified to be the most abundant mineral in coatings or surfaces of open fractures.

Calculations with measured values for pH and alkalinity indicate that pCO_2 decreases with depth from 10^{-2} to $10^{-4.5}$ atm. at Olkiluoto. Calculated pCO_2 values at Forsmark also tend to decrease with depth, but there is a small difference between the ranges calculated for the less transmissive ‘footwall’ fracture domain in the northern part of the area (10^{-3} to 10^{-5} atm) and for the ‘hanging wall’ domains in the rest of the area (10^{-2} to 10^{-4} atm). This is attributed to the difference in groundwater mixing in the two domains.

Reaction with aluminosilicate minerals is considered to be a minor process for pH buffering relative to reaction with calcite in the interpretation of both sites. However, models including aluminosilicate reactions and cation exchange as well as calcite equilibrium to account fully for the systematic variations and evolution of pH, alkalinity and relative cation concentrations, e.g. Ca:Na, have not been presented for either site.

5.6 Compositions of rock matrix pore waters in relation to fracture waters

The strong contrast in hydraulic properties between rock mass and transmissive fractures has already been discussed in Section 4.6. The resulting differences and lack of equilibration in hydrochemical compositions is a recent and striking finding, the implications of which for hydrogeological and hydrochemical interpretation are not yet fully understood.

Profiles of pore water Cl^- concentration and stable isotope ratios have been measured for two drillholes at Olkiluoto and for four drillholes at Forsmark.

Estimated Cl^- concentrations in pore waters are calculated from results of leaching tests coupled with data for porosity and an estimation of the proportion that is anion-accessible. Pore water Cl^-

concentrations at Olkiluoto are systematically more dilute than fracture waters at corresponding depths below about 100 m. The divergence, which appears to be much greater than the potential error on pore water data, increases substantially below about 300 m so that pore waters have brackish salinity whilst fracture waters are saline. For example, Cl^- is about 500 mg/L in pore waters and is about 19000 mg/L in fracture waters at 600 m depth in borehole KR47. This difference has implications for hydrogeological and hydrochemical modeling of future groundwater conditions. Paleohydrogeological concepts and modeling that might explain these observations and thus assess the implications for long term evolution have not yet been comprehensively presented by Posiva.

Estimated pore water Cl^- concentrations in boreholes at Forsmark show different patterns for locations in the 'footwall' and 'hanging wall' rock domains with respect to sub-horizontal deformation zone A2. Porewater Cl^- concentrations are generally lower than Cl^- in fracture waters but the contrast is greater and the porewater Cl^- values are lower (<1500 mg/L down to 550 m depth) in the boreholes that are located in the hanging wall domain (KFM02B and 06A upper part) versus boreholes in the footwall domain (KFM01D, 06A lower part and 08C).

Water stable isotopic compositions ($^{18}O/^{16}O$) are heavier for pore waters than for fracture waters in the footwall rock domain samples at Forsmark. Isotopic compositions of pore waters in hanging wall rock at Forsmark are similar to those for fracture waters. Isotopic compositions of pore waters and fracture waters at Olkiluoto have so far been found to have a similar relationship.

SKB have inferred that pore waters in the hanging wall rock domain at Forsmark have equilibrated relatively recently with pre-Littorina fracture waters because of a higher frequency of vertical fracturing whereas pore waters in the less fractured footwall domain are much older, *i.e.* are pre-glacial.

The implications of these findings regarding pore water compositions are that the solute transport and water exchange behavior of rock at Olkiluoto and in the footwall at Forsmark are quite similar. They also indicate that both systems had long periods of deep circulation, prior to glaciation, of water that was less saline than is presently seen in the fracture system, suggesting that groundwaters in the long-term future could also revert to low salinities. An additional consequence of these relatively dilute pore waters is that they should be taken into account in models of future evolution of hydraulic and hydrochemical conditions.

5.7 Isotopic and dissolved helium compositions and groundwater ages

Brackish SO_4 rich groundwaters at Olkiluoto have carbon-14 (^{14}C) contents ≤50 pmC which is consistent with the dominant Littorina origin attributed to them (Posiva, 2009). Brackish-Cl and saline groundwaters have ^{14}C contents from 5 to 22 pmC.

A component of glacial melt water (or other 'cold climate' water) is indicated by the $^{18}O/^{16}O$ ratio which increases with depth from -15 to -9‰ in brackish waters to -13 to -10‰ in saline water at Olkiluoto. The depth to which glacial water penetrated and mixed with deep pre-glacial saline water at Olkiluoto has been the subject of changing interpretation. This issue is tied in to Posiva's concept of 'subglacial initial water' which represents the inferred composition of groundwater in the system prior to the last glaciation (see Section 5.8 for further comments on this). Preliminary modelling assumed that this composition was 3500 mg/L Cl^- and -12‰ $\delta^{18}O$ which in turn indicated 10–20% of glacial water in the brackish-Cl and saline groundwaters. However this mixing calculation has been revised using slightly more dilute 'subglacial initial water' with 3000 mg/L Cl^- which thus leads to a lower degree of deep penetration of glacial water being modelled. Posiva's conclusion on this and on the related issue of Littorina water mixing is that there are only 'minor' proportions of Littorina and glacial water in the brackish-Cl and saline groundwaters below 300 m depth. The uncertainty on this is relatively large and is evidently dependent on assumptions about the compositions of various end-members. The reasoning and evidence for an assumed subglacial water composition needs to be clear if it is the basis for conclusions about these other aspects of palaeohydrogeology.

The content of dissolved helium (^4He) increases generally with depth to >10 mL/L in saline groundwater. This supports the ^{14}C pattern qualitatively but is not interpretable, even semi-quantitatively, in terms of age for the saline water component in the deep mixed groundwaters. 8 analyses of ^{36}Cl

data are reported for various groundwater types at Olkiluoto; the $^{36}Cl/Cl$ ratios are all low, $\leq 25\times10^{-15}$, and the interpretation with respect to water ages is unclear.

Brackish groundwaters between 150 and 500 m depth at Forsmark have ^{14}C contents mostly in the range 5–30 pmC (Laaksoharju et al, 2008). This suggests a range of groundwater ages from post-glacial to older for brackish non-marine waters; post-glacial ages are consistent with the Littorina origin for the bulk of brackish-marine waters. ^{14}C data for brackish-marine groundwaters are supplemented by measurements on dissolved organic carbon (DOC) for three samples which contain 45–53 pmC, corresponding to contents in TIC of 13–17 pmC. The ^{14}C(DOC) data support the post-glacial age, 5000–6000 y, and Littorina origin for the brackish-marine waters.

There seems to be a more complex picture at Forsmark than at Olkiluoto for the distribution of water of glacial or other cold-climate origins. $^{18}O/^{16}O$ ratios range between -14 and -8‰ $\delta^{18}O$ (with one measurement of -16‰ in a brackish-marine water). There is a slight overall tendency towards lighter $\delta^{18}O$ values with increasing depth which suggest that glacial water is a component of most or all of the groundwaters and that it penetrated to >500 m depth at Forsmark.

Helium (^4He) contents of brackish groundwaters at Forsmark are around 1 mL/L whilst those of saline groundwaters are >10 mL/L. These values are comparable with helium contents of saline groundwaters at Olkiluoto.

5.8 Groundwater end-members and mixing

Water types at Olkiluoto change from Ca-Na-HCO_3-SO_4 and Ca-Na-HCO_3 in shallow dilute groundwaters, to Na-(Ca)-Cl-(SO_4) in brackish-SO_4 waters, to Na-Ca-Cl and Ca-Na-Cl in the deep brackish-Cl and saline groundwaters (see Section 5.4) (Posiva, 2009). Mixing of different end-member component waters with distinct origins at Olkiluoto has been interpreted by Posiva using a mass-balance and mixing-reaction inverse modelling method which attempts to take into account non-conservative solute changes due to water-rock reaction as well as mixing of conservative solutes.

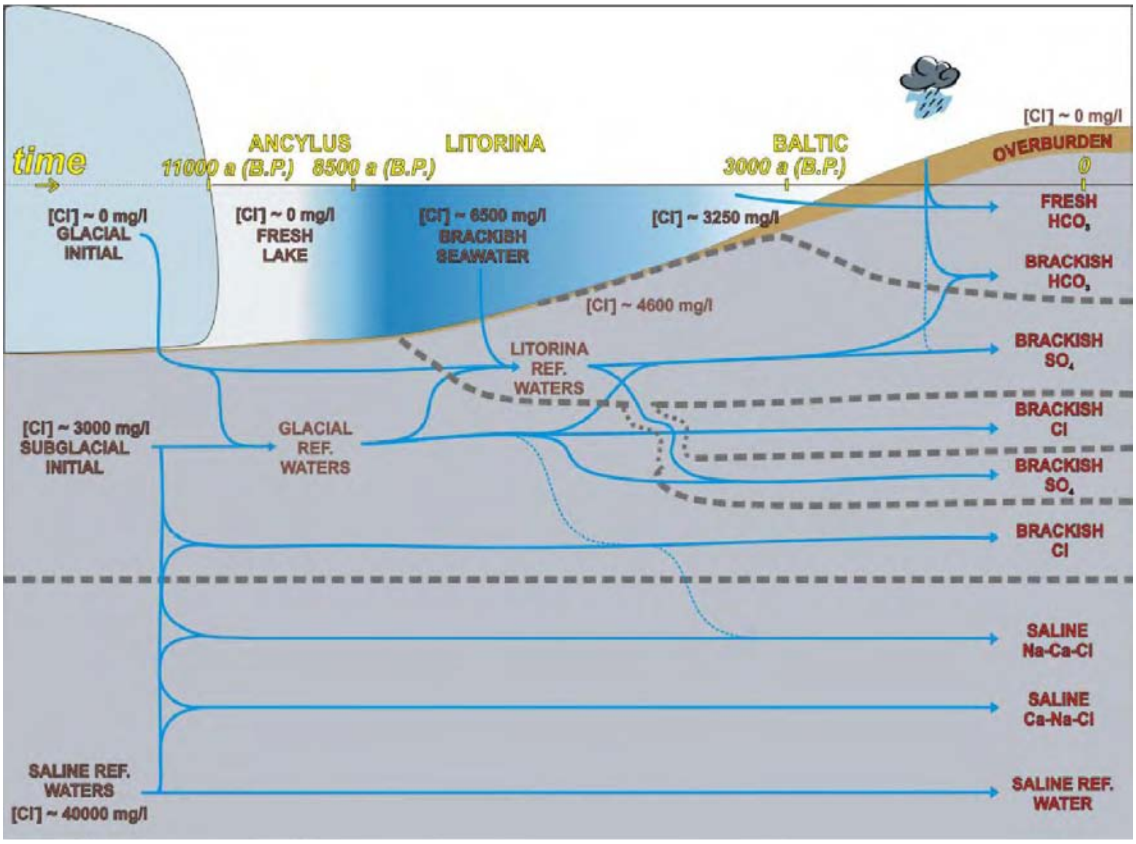


Figure 16. Schematic representation of interpreted initial and boundary conditions at Olkiluoto since the last glacial period (from Posiva, 2009, Figure 7-12). Note that the time scale (horizontal axis of the plot) in terms of years before present is not linear.

Mixing is interpreted in terms of proportions of five reference waters: meteoric, Littorina, glacial, subglacial and saline (Pitkänen et al, 2003). The 'meteoric' reference water dominates down to about 150 m depth, below which substantial proportions of 'subglacial' and 'Littorina' are mixed down to about 300 m. 'Subglacial' dominates from about 200 m to 600 m depth, below which 'saline' dominates (Figure 16). It is commented in the previous section that the significance and reality of the 'subglacial' end member is arguable and using it in mixing modelling may obscure the presence of glacial-origin and deep-saline waters.

Br/Cl ratios in groundwaters at Olkiluoto tend to increase with depth, from 0.002–0.005 in brackish-SO_4 waters, to 0.004–0.007 in brackish-Cl waters and 0.006–0.0085 in saline waters (Posiva, 2009). This pattern is consistent with the marine origin of salinity in brackish-SO_4 waters evolving towards a non-marine origin for salinity in deep bedrock groundwaters in which Br/Cl ratio has increased due to water-rock reaction. Br/Cl ratios in pore waters at Olkiluoto tend to mirror this pattern in fracture waters.

Water types at Forsmark change from Na-(Ca)-HCO_3-(SO_4) in shallow fresh groundwaters, to Na-Ca-Mg-Cl-SO_4 in brackish marine waters to Ca-Na-Cl in brackish non-marine and saline waters. The overall pattern of water types is therefore similar to that at Olkiluoto.

Mixing of end-member water components at Forsmark has been interpreted by SKB on the basis of a conceptual model for post-glacial groundwater evolution (Fig. 17) and statistical analysis of water

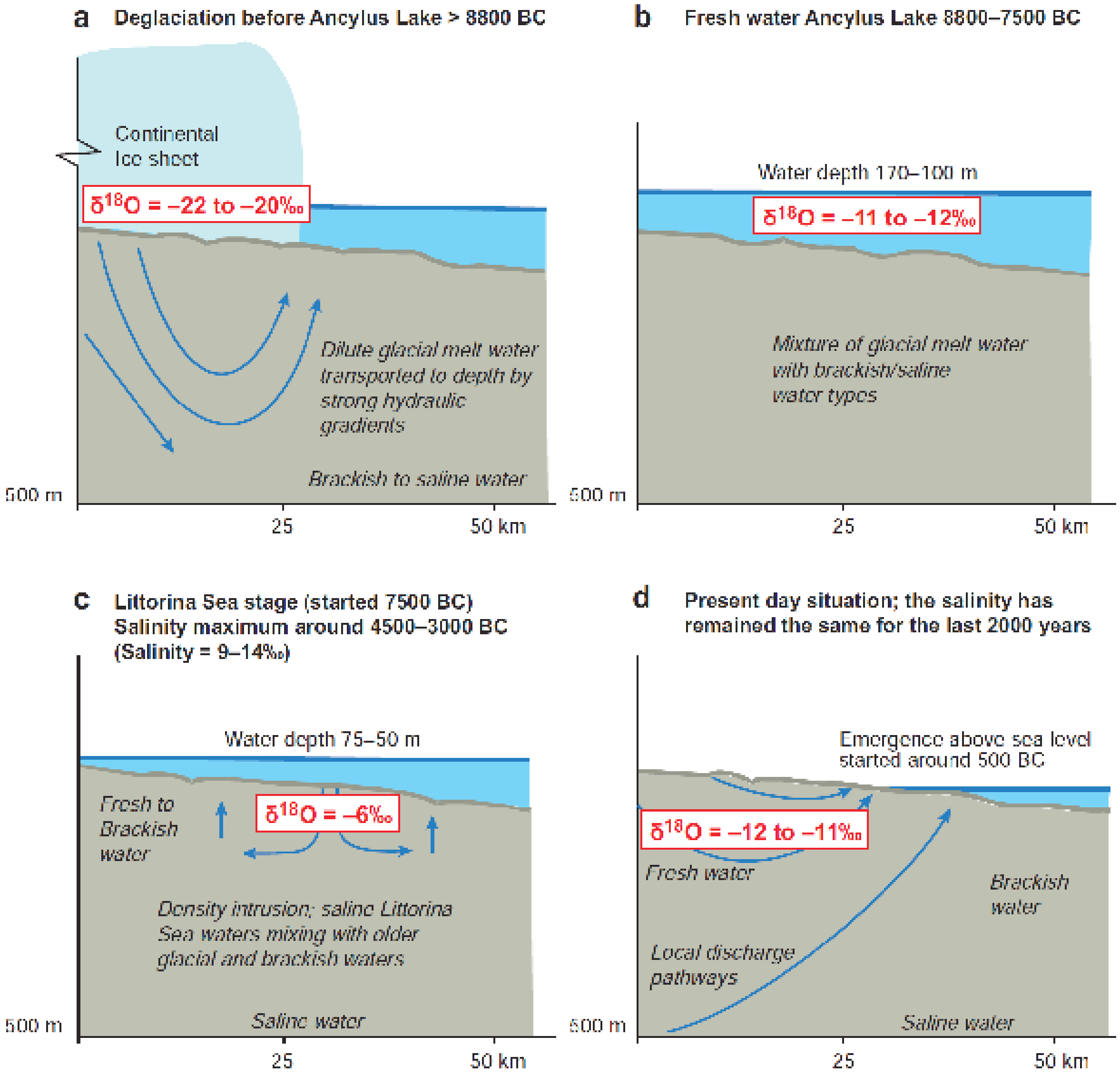


Figure 17. Conceptual model for post-glacial groundwater evolution at Forsmark (from SKB, 2008, Figure 3-9).

chemical and isotopic compositions and, unlike the method used for Olkiluoto data, has not quantitatively taken account of geochemical reactions in the model. The principal components analysis (PCA) tool 'M3' has been used by SKB; this method is influenced most strongly by compositions of conservative solutes and water isotopes whilst solutes affected by water-rock reactions have a secondary effect on the PCA analysis and cannot be resolved in terms of explicit reactions and mass transfers.

Preliminary modelling with M3 was done with three different sets of end-member waters; the preferred set of end members used for the final analyses comprises: altered meteoric, Littorina, glacial, and deep saline (Laaksoharju et al, 2008). The basic premise of the mixing modelling and analysis of end-member proportions for Forsmark is therefore rather different from that for Olkiluoto. The resulting end-member proportions for Forsmark groundwaters are: (i) altered meteoric decreasing with depth from 95% maximum in shallow groundwaters to <10% at >500 m; (ii) Littorina decreasing with depth from 55% maximum to <10%; (iii) glacial (+old meteoric) increasing with depth from 10% to 70%; (iv) deep saline between 10–30% in saline groundwaters.

As at Olkiluoto, Br/Cl increases with depth at Forsmark from 0.003–0.005 in brackish-marine waters to 0.008–0.014 in brackish-saline non-marine waters. The brackish-marine Br/Cl ratios are similar to those at Olkiluoto, as expected, but the non-marine brackish and saline waters have rather higher Br/Cl ratios suggesting that a greater degree of water-rock reaction has enhanced Br in the deeper groundwaters at Forsmark.

5.9 Abundance and composition of colloids and DOC

Water samples have been collected for colloid analyses in the 'groundwater stations' PVA 1 and 5 (at chainages approx 200 and 2400, *i.e.* at depths of about 20 and 240 m) in the ONKALO tunnel at Olkiluoto (Järvinen et al, 2011). Particle counting and analyses of filtered colloids indicated concentrations of 0.5 and 0.15 µg/L respectively. Mineral and chemical compositions of these colloids have not been reported. Dissolved organic carbon (DOC) contents of groundwaters at Olkiluoto are reported to be 0–25 mg/L down to 100 m depth, <10 mg/L between 100–300 m (except 1 sample with 40 mg/L), and up to about 20 mg/L (1 sample with 37 mg/L) from 300–800 m (Posiva, 2009). However it is noted that Posiva casts doubt on the validity of these data, suspecting contamination of samples.

Colloids contents in groundwaters at Forsmark are reported to be in the range 0–160 µg/L, having approx values 160, 60 and 20 µg/L in 3 samples from depths of 112, 176 and 215 m, and <20 µg/L in saline waters at >600 m depth (Laaksoharju et al, 2008). Colloidal particle counts are mostly 2–6×10^5 per mL, with higher outlier values in two boreholes. Information about mineral and chemical compositions is contradictory. Analysis of filtered/fractionated particles indicates Fe and S compounds, whilst LIBD/EDX analysis indicates Al, Si and Fe compounds. Therefore some colloids concentrations at Forsmark are much higher than in the two samplings done at Olkiluoto; however it is possible that this is attributable to the greater difficulty in obtaining representative samples for *in-situ* colloids from surface-based boreholes than from seepages into short boreholes underground in ONKALO.

DOC concentrations in Forsmark groundwaters are reported to be between 5 and 15 mg/L in shallow groundwaters (0–100 m depth; 1 outlier sample with 35 mg/L) and <5 mg/L from 100–1000 m (2 outlier samples with 10 and 15 mg/L). These ranges of DOC at Forsmark are fairly similar to those at Olkiluoto. The evidence suggests that, at both sites, DOC is not contributing to colloids formation.

5.10 Stable S and C isotope ratios

δ^{34}S (SO_4) values in groundwaters at Olkiluoto are in the ranges: (i) +22 to +27‰ for brackish-SO_4 waters; (ii) +16 to +31‰ for brackish-Cl waters; (iii) +20 to +33‰ for saline waters (Posiva, 2009). It is noted that SO_4 concentrations in the second and third categories are very low and thus errors on δ^{34}S data are almost certainly higher.

δ^{34}S (SO_4) values in groundwaters at Forsmark are in the ranges: (i) +20 to +32‰ for brackish marine waters (2 outliers at +16 and +38‰); (ii) +24 to +38‰ for brackish and saline non-marine waters (Laaksoharju et al, 2008). There is a general trend towards higher δ^{34}S values with increasing depth and salinity, though there is substantial scatter. There is not a clear relationship to SO_4^{2-} concentrations, *i.e.* as SO_4^{2-} decreases in the saline groundwaters, some δ^{34}S values are higher (e.g. up to +38‰) but equally other lower-SO_4 waters have $\delta^{34}S$ around +24‰. Therefore a simple Rayleigh fractionation of $^{34}S/^{32}S$ due to SO_4-HS reduction does not account for all $\delta^{34}S$ values at Forsmark. SKB infer that SO_4 reduction under open or partially open conditions, in which some SO_4 has been replenished or recycled as reduction proceeds, might account for the complex pattern at Forsmark.

The same interpretation seems appropriate for the $\delta^{34}S$ data for Olkiluoto groundwaters in which SO_4 concentrations in saline waters go to even lower values. Microbial SO_4 reduction is known to occur at both sites, so the geochemical processes affecting SO_4 appear to be similar in both cases but are not fully understood.

Values of $\delta^{13}C$ for dissolved inorganic carbon (DIC, primarily HCO_3^-) in groundwaters at Olkiluoto are in the range -25 to -10‰. $\delta^{13}C$(DIC) values in groundwaters at Forsmark are mostly in the range -16 to -4‰ and are inversely correlated with ^{14}C, *i.e.* young shallow groundwaters have lower $\delta^{13}C$ values whilst older brackish waters, mostly of marine Littorina origin, have higher $\delta^{13}C$ around -5‰.

The trends towards higher $\delta^{13}C$ values indicate that water-rock reaction is occurring, including calcite precipitation. It is noted that DIC contents of groundwaters at both sites decrease sharply as salinity increases, indicating that calcite precipitation probably occurs and this would be one factor causing $^{13}C/^{12}C$ fractionation. The difference in maximum $\delta^{13}C$ values between Olkiluoto and Forsmark suggests that water-rock reaction has been more prevalent at Forsmark, but SKB does not have a detailed model for the relevant processes.

5.11 Sorbing minerals in fractures and matrix, also matrix porosity and diffusion

Calcite, clays and sulphides are common as fracture minerals at all depths at Olkiluoto (Posiva, 2009). The main gouge fillings in open fractures seen in the ONKALO tunnel are quartz, chlorite, illite, kaolinite, montmorillonite and calcite. The mixing-reactive transport geochemical model for Olkiluoto has the main mass transfers occurring with calcite, pyrite, plagioclase, kaolinite and quartz plus general cation exchange. Therefore these mineral phases are likely to be the most available for radionuclide retardation in transmissive fractures at Olkiluoto. The conceptual model for radionuclide retention and porosity at Olkiluoto has three ‘immobile zones’: unaltered rock, altered rock, and fracture fillings and coatings. The main fracture filling minerals are typically 0.3–0.4 mm thick. Porosity in the rock matrix is estimated to vary with distance from transmissive fractures, with values of 5% at up to 10 mm distances and 1% at more than 10 mm from a fracture.

The most common fracture minerals at Forsmark are chlorite, calcite, laumontite/epidote/ prehnite, sulphide minerals and iron oxides (Sandström et al, 2008; Laaksoharju et al, 2008).

It is uncertain whether the differences between this assemblage and that for Olkiluoto are real and substantial, or whether it is an analytical detection and identification issue. On the face of it, Olkiluoto is distinct from Forsmark in having more clays and in zeolite-group minerals, epidote and iron oxide minerals being absent, or not detected. The porosity of rock matrix at Forsmark varies from 0.2–1.04% (median ca. 0.4%) for all rock types except the vuggy granite (Sandström and Stephens, 2009).

5.12 Hydrogeochemistry of natural uranium

A few water samples from specific boreholes at Forsmark have anomalously higher uranium (U) concentrations (Laaksoharju et al, 2008). These high U occurrences are linked with high U concentrations in corresponding drillcore samples, so SKB interprets these as local hydrogeochemical anomalies related to rock history. It is found that a proportion of the U in these water samples is associated with colloids. As far as is known, there is no similar anomaly in natural U distribution in Olkiluoto rocks and groundwaters.

Table 7. Comparison of hydrogeochemical characteristics of sites.

Property	Olkiluoto	Forsmark	Implications
Distribution and sources of salinity	Maximum salinity down to ca1000m: 84000 mg/L TDS, ca 52000 mg/L Cl^-; more homogeneous distribution and trend versus depth.	Maximum salinity down to ca1000m (central/northwest sectors): 17000/24000 mg/L TDS, 10000/15000 mg/L Cl^-; more heterogeneous distribution according to fracture domains and sectors.	Up-coning from below a repository at Olkiluoto would pose a greater hazard to the EBS (i.e. buffer swelling pressure, corrosion rate) than at Forsmark due to the proximity of significantly higher salinity and the uncertainty for salinity at >1000m
	Brackish-SO_4 water at 100–300m (≤5000 mg/L Cl^-, 30–250 mg/L Mg^{2+}, ≤580 mg/L SO_4^{2-})	Brackish-marine water at 60-600m (<6000 mg/L Cl^-, 10-250 mg/L Mg^{2+}, ≤550 mg/L SO_4^{2-})	Deeper Littorina penetration at Forsmark suggests higher vertical connectivity
	Brackish-Cl water at 300–450m (≤7000 mg/L Cl^-, ≤80 mg/L Mg^{2+}, <100 mg/L SO_4^{2-})	Brackish non-marine water at >350m (>5000 mg/L Cl^-, 10-80 mg/L Mg^{2+}, ≤200 mg/L SO_4^{2-})	Generally similar hydrochemistry at proposed repository depths for both sites; also transition to less conductive system
	Saline water at >450m (6000–45000 mg/L Cl^-, 0–130 mg/L Mg^{2+}, <10 mg/L SO_4^{2-})	Saline water at >500m (6000-15000 mg/L Cl^-, 0-20 mg/L Mg^{2+}, 20-150 mg/L SO_4^{2-})	The salinity gradient is steeper below proposed repository depth at Olkiluoto
	Interpreted mixing model end-members are: meteoric, Littorina, glacial, 'subglacial', saline	Interpreted mixing model end-members are: altered meteoric, Littorina, glacial, deep saline	Different end-members so mixing models are not comparable. Large uncertainties in water proportions propagate into palaeohydrogeological models
	Br/Cl increases with depth: 0.002–0.005 in brackish-SO_4, 0.004–0.007 in brackish-Cl, 0.006–0.0085 in saline water	Br/Cl increase with depth: 0.003–0.005 in brackish-marine, 0.008–0.014 in brackish non-marine	Similarities confirm Littorina water source for brackish waters at both sites; higher Br/Cl characterizes deep saline waters
Post-glacial palaeo-hydrogeology	Maximum Littorina salinity 5600 mg/L Cl^-	Maximum Littorina salinity 8400 mg/L	Unclear whether this difference is real or an interpretation artefact
	Sub-aerial emergence at 3000–2500 y ago	Sub-aerial emergence at 2500 y ago	Similar periods of meteoric water infiltration
	"Minor proportions" only of Littorina and glacial waters at >300m	Littorina penetrated to ≤600m; glacial water to >500m	Suggests that Forsmark has higher vertical conductivity from surface, but these interpretations have large uncertainties
Redox and biogeo-chemistry	Eh +100 to -400 mV	Eh -143 to -281 mV	Inferred absence of dissolved oxygen at both sites; redox control and buffering for Olkiluoto are poorly characterized
	HS^- <1 mg/L at <250m & >350m, 0–12 mg/L at 250-350m	HS^- mostly <0.1 mg/L at 50–1000m except for 5 samples 0.2–1.6 mg/L	Corrodant HS^- concentrations are generally low at proposed repository depths at both sites, but there are spot anomalies at both sites that are not explained
	Fe^{2+} mostly 0–1 mg/L at >100m	Fe^{2+} mostly <3 mg/L at <300m, <2.5 mg/L at >300m	Additional evidence for uniformly reducing conditions
	CH_4 <10 mL/L at <300m, then increases with depth to ~1000 mL/L at 1000m	CH_4 mostly <0.10 mL/L	Large difference; source of much higher CH_4 at Olkiluoto is not known, nor is possible magnitude of future changes
	H_2 increases with depth from μL/L to mL/L magnitudes	H_2 below detection (3 μL/L) to 370 μL/L	Slightly higher H_2 at Olkiluoto but may be sampling artifact
	DOC ≤20 mg/L at >300m (contaminated?)	DOC mostly <5 mg/L at >100m	Similar low levels of dissolved organics at both sites, i.e. low significance for radionuclide speciation
	Microbial TNC 10^4–10^5 cells/mL at >100m; MPNs for all groups peaks at 250–350m; acetogens are dominant group	Microbial TNC 10^4–10^6 cells/mL; MPNs show no pattern; acetogens are dominant group, methanogens are very sparse; MPN for SRB are possibly correlated with Eh	Similar microbial data for both sites, but uncertain how representative data are; biogeochemical model and implications for redox remain unclear
pH and dissolved inorganic carbon	pH 7 to 7.5 in brackish-HCO_3 water, ≤7.5 in brackish-SO_4, ≤8.2 in brackish-Cl, decreasing 8 to 7.5 in saline water as TDS increases	pH 7.3 to 8.2 in brackish marine water, 7.0 to 8.5 in brackish non-marine and saline water	Similar for both sites, pH variation is well within safety function requirement; buffering in both cases is primarily due to calcite
	HCO_3^- inversely correlated with salinity; <2 meq/L in brackish-SO_4 water, <1 meq/L in brackish-Cl and saline water	HCO_3^- inversely correlated with salinity; <3 meq/L in brackish marine water, <1 meq/L in brackish non-marine and saline water	Similar values, consistent with the pH buffering model

Property	Olkiluoto	Forsmark	Implications
	pCO$_2$ decreases with depth from 10^2 to $10^{-4.5}$ atm	pCO$_2$ decreases from 10^{-3} to 10^{-5} atm in footwall, from 10^{-2} to 10^{-4} in hanging wall	Similar values, consistent with the pH buffering model
Cations hydro-chemistry	Increasing vs depth to max at 1000m: Na$^+$ ~10000 mg/L, Ca^{2+} ~18000 mg/L, Sr^{2+} ~190 mg/L	Increasing vs depth to max at 1000m: Na$^+$ ~2200 mg/L, Ca^{2+} ~4000 mg/L (>4000 mg/L in northern sector), Sr^{2+} ~70 mg/L	Na versus Ca, Mg and K differences indicate that hydrogeochemical evolution models for the two sites are slightly different; neither SDM has a full model for aluminosilicate reactions and cation exchange
	Mg^{2+} reaches maximum 250–300 mg/L in brackish-SO$_4$ water, generally <60 mg/L in saline water except 100–130 mg/L in deepest most saline water	Mg^{2+} reaches max 250–300 mg/L in brackish-marine water, 10-80 mg/L in brackish non-marine decreasing to <20 mg/L in saline water	
	K$^+$ varying vs depth with max ~29 mg/L at 1000m	K$^+$ 5–68 mg/L at <100m, varying vs depth decreasing to ~10 mg/L at 1000m	
Pore waters	Cl$^-$ 500 mg/L at 600m (KR47) vs 19000 mg/L in fracture water	Cl$^-$ hanging wall domain: 3000 mg/L at 450m, 1000 mg/L at 550m vs 5500 mg/L in fracture water; footwall domain: <4000 mg/L to 600m vs 7000 mg/L in fracture water, <11500 mg/L to 850m (except peak of 15000 mg/L at 650m)	Dilute pore waters have hydraulic and hydrochemical effects on future groundwater evolution. Pore water chloride and water isotopic compositions have been included in palaeohydrogeological model for Forsmark but not yet for Olkiluoto
	δ^{18}O lighter than δ^{18}O of fracture waters at ≤100m; heavier than δ^{18}O of fracture waters at >300m	δ^{18}O heavier than δ^{18}O of fracture waters in footwall domain; δ^{18}O are similar in hanging wall domain	
Water ages	^{14}C ≤50 pmC in brackish-SO$_4$ water, 5–22 pmC in brackish-Cl and saline waters	^{14}C 5–30 pmC in brackish waters between 150–500m; ^{14}C(DOC) 45–53 pmC in brackish-marine waters	Consistent with Littorina source for brackish water at both sites. Deeper water ages cannot be resolved quantitatively due to mixing
	δ^{18}O -15 to -9‰ in brackish waters, -13 to -10‰ in saline waters	δ^{18}O -14 to -8‰ in brackish waters (except one sample at -16‰ in brackish marine), decreasing slightly vs depth to >500m	Additional evidence for complicated water mixing and palaeohydrogeology at both sites
	^{4}He increases generally to >10 mL/L in saline water	^{4}He increases from 1 to >10 mL/L from brackish to saline waters	Similar for both sites, but cannot be quantitatively interpreted
Colloids	0.15 and 0.5 µg/L by two methods	0-160 µg/L (lower values at >600m); 2–6×10^5 particles/mL	Data for the two sites are probably not comparable because of different sampling sources
Uranium hydro-chemistry	Dissolved uranium: 0–20 µg/L at 0–100m, <5 µg/L at 100–200m, <2 µg/L at >200m	Dissolved uranium: 0–20 µg/L at 0–100m, 0–40 µg/L at 100–600m, <5 µg/L at >600m; high anomalies 50–150 µg/L at 490–630m correlated with high U in drill cores	Uranium data are consistent with expected redox conditions at both sites except for anomalous localized high concentrations at Forsmark
S and C stable isotopes	δ^{34}S(SO$_4$) +22 to +27‰ in brackish-SO$_4$, +16 to +31‰ in brackish-Cl, +20 to +33‰ in saline water	δ^{34}S(SO$_4$) mostly +20 to +32‰ in brackish marine (two outliers at +16 and +38‰), +24 to +38‰ in brackish non-marine and saline waters	Similar for both sites and generally consistent with hydrogeochemical model for sulphate reduction as source of sulphide
	δ^{13}C(DIC) -25 to -10‰	δ^{13}C(DIC) -16 to -4‰	Additional evidence for water-rock reaction, with greater degree of reaction at Forsmark
Rock fabric and retention model	Fracture minerals: calcite, clays, sulphides; gouge minerals: quartz, chlorite, illite, kaolinite, montmorillonite, calcite	Fracture minerals: chlorite, calcite, laumontite/epidote/prehnite, sulphides, iron oxides	Some minerals e.g. calcite, chlorite, pyrite, clays are common in both sites. There are apparent differences e.g. zeolite-epidote and iron oxide at Forsmark only, but this may be an analytical artifact
	Porosity of rock matrix: 5% within 10mm of fracture, 1% at >10mm	Porosity of rock matrix: varies from 0.2–1.04% (median ca. 0.4%) for all rock types except the vuggy granite.	Different porosities correspond to different conceptual models of rock alteration used in the retention models

6 Mechanical properties

Comparisons of the rock mechanical properties of the two sites are presented in the following sections:

6.1	Rock stresses at disposal depth
6.2	Properties of intact rock
6.3	Fracture properties
6.4	Rock mass deformability and strength
6.5	Mechanical properties of brittle zones
6.6	Bedrock stability

6.1 Rock stresses at proposed disposal depths

Rock stresses have been measured at both sites using multiple methods including overcoring, hydraulic fracturing, and hydraulic pressurization of pre-existing fractures, as well as semi-quantitative methods (observations of core disking and wellbore breakouts). At both sites, considerable scatter in data has been encountered both between and within particular methods, resulting in ambiguity regarding the stresses at depth (see Figures 18 and 19).

At Olkiluoto, convergence measurements in underground openings (shafts and tunnels) have been employed, along with Kaiser Effect measurements (Lehtonen *et al.*, 2012). This last method is based on the observation that rocks retain a "memory" of the highest stress that they have been subject to in any given direction, under conditions of brittle deformation (Goodman, 1963). The method involves axial loading of rock cylinders taken from cores, until acoustic emissions indicate that the highest previous stress in that orientation has been exceeded. In this way a three-dimensional stress tensor can be deduced. However, for rocks such as at Olkiluoto which have been subjected to a long and complex brittle-deformation history, there is uncertainty as to whether the results are indicative of the modern state of stress, or some past state of higher stress (for example, ice loading during past glaciations).

At Forsmark, localized core disking was seen in only a few short sections of ordinary (solid, cylindrical) core during drilling to depths of 1000 m, which was interpreted as indicating maximum horizontal stresses possibly up to 44 MPa at 500 m depth (Martin, 2007, p. 30). Core disking was more regularly encountered in the form of "ring-core disking" during attempts at overcoring stress measurements, in the hollow cylinders of rock that are created during the overcoring process. This phenomenon, together with microcracking as discussed by Martin (2007, p. 45–46), limited the usefulness of overcoring stress measurement data from depths greater than 300 m. To overcome the problems encountered with the overcoring stress measurements in the target area SKB decided to use the old overcoring stress data from a deep borehole (DBT 1 in Figure 19) adjacent to reactor 3 of the Forsmark nuclear power plant and located in the metavolcanic rocks outside the granitic lens.

At Forsmark, the validity of hydraulic fracturing results has been questioned by the site investigation team, due to suspicion that fractures have propagated horizontally rather than vertically in the direction of the minimum horizontal stress. Two different models for rock stresses at depth have been presented by SKB's experts (Martin, 2007; Ask *et al.*, 2007), giving different weight to these data, see Figure 19. Depending on which of these models is chosen, the stresses at proposed repository depths of 400 m to 500 m at Forsmark are either higher or lower than the stresses at Olkiluoto (Table 8). At Forsmark, the overcoring stress data are higher than data obtained with hydraulic methods, which is normally the situation because of the difference in scale of volume involved. At Olkiluoto, there is a trend of magnitude of overcoring data being somewhat lower or equal data obtained from hydraulic methods.

Olkiluoto is interpreted as being in a thrust-faulting regime, with horizontal stresses greater than the vertical stress. This is supported by over-

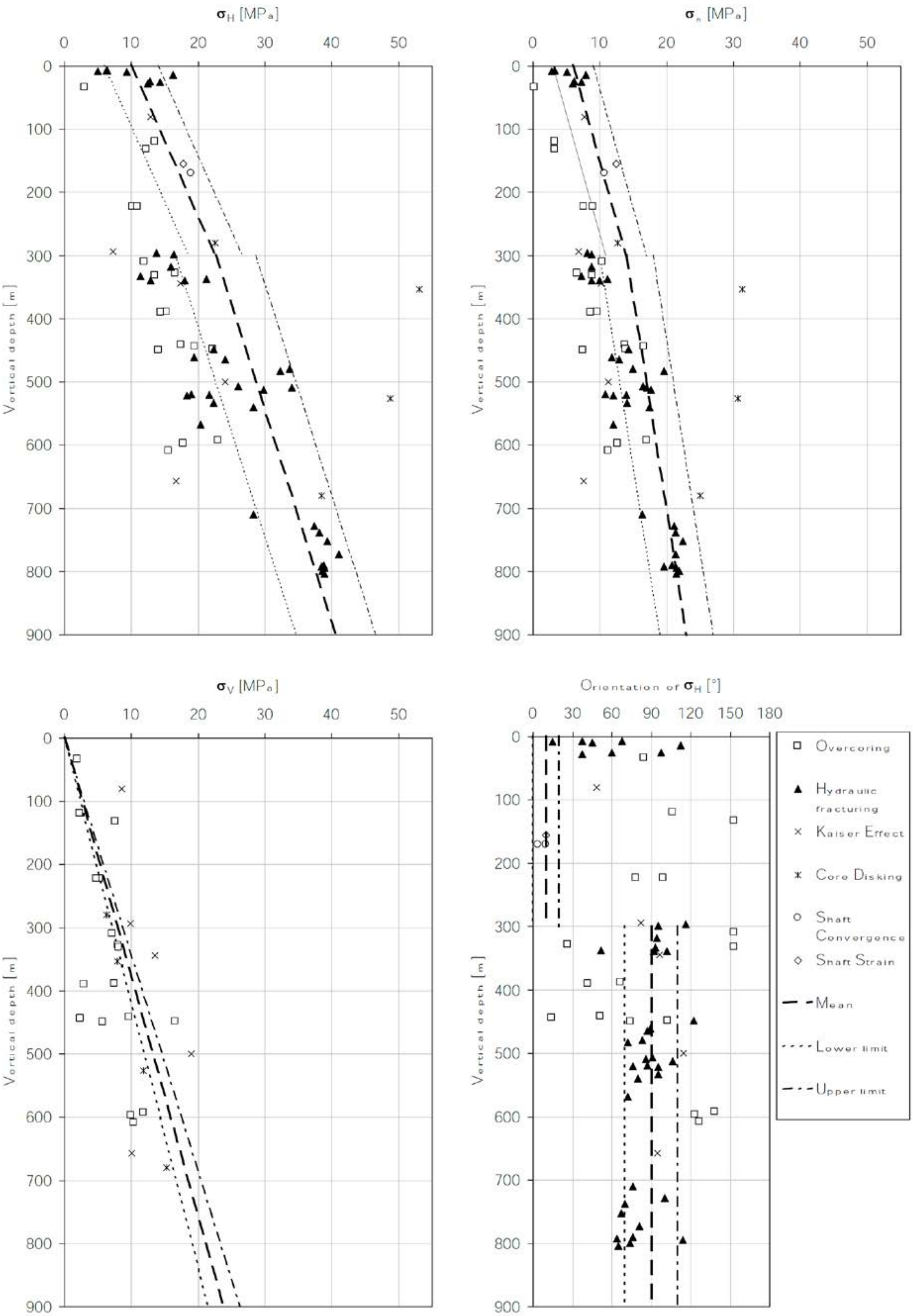


Figure 18. Magnitude of horizontal and vertical stress and orientation of maximum horizontal stress versus depth at Olkiluoto. The mean, upper and lower limit of a stress model with two stress domains, one from ground surface down to 300 m and one from 300 m down to 900 m depth. After Posiva 2009a.

Table 8. Comparison of stress models at Olkiluoto and Forsmark, evaluated at 400 m and 500 m depths.

Site	Depth (m)	Maximum horizontal stress σ_H (MPa)	Minimum horizontal stress σ_h (MPa)	Vertical stress σ_v (MPa)	Direction of σ_H
Olkiluoto	400	25.6	15.5	10.6	E-W (90°)
Forsmark (Martin, 2007)	400	38.7	20.4	10.6	S35E (145°)
Forsmark (Ask et al., 2007)	400	19.2	9.3	10.4	S56E (124°)
Olkiluoto	500	28.6	17.0	13.2	E-W (90°)
Forsmark (Martin, 2007)	500	41.0	23.2	13.2	S35E (145°)
Forsmark (Ask et al., 2007)	500	22.7	10.2	13.0	S56E (124°)

coring and Kaiser Effect measurements which show that the minimum principal stress is approximately aligned with vertical, although there is considerable scatter (Figure 18). Forsmark is similarly interpreted as being in a thrust-faulting regime by Martin (2007). However the alternative model for Forsmark (Ask *et al.*, 2007) indicates a strike-slip faulting regime (NNW left-lateral or ENE right-lateral), since the minimum horizontal stress is interpreted as being lower than the vertical stress.

An unusual feature of the model for Olkiluoto is that the magnitudes of maximum and minimum horizontal stress are continuous with depth and with different gradients, but the direction of maxi-

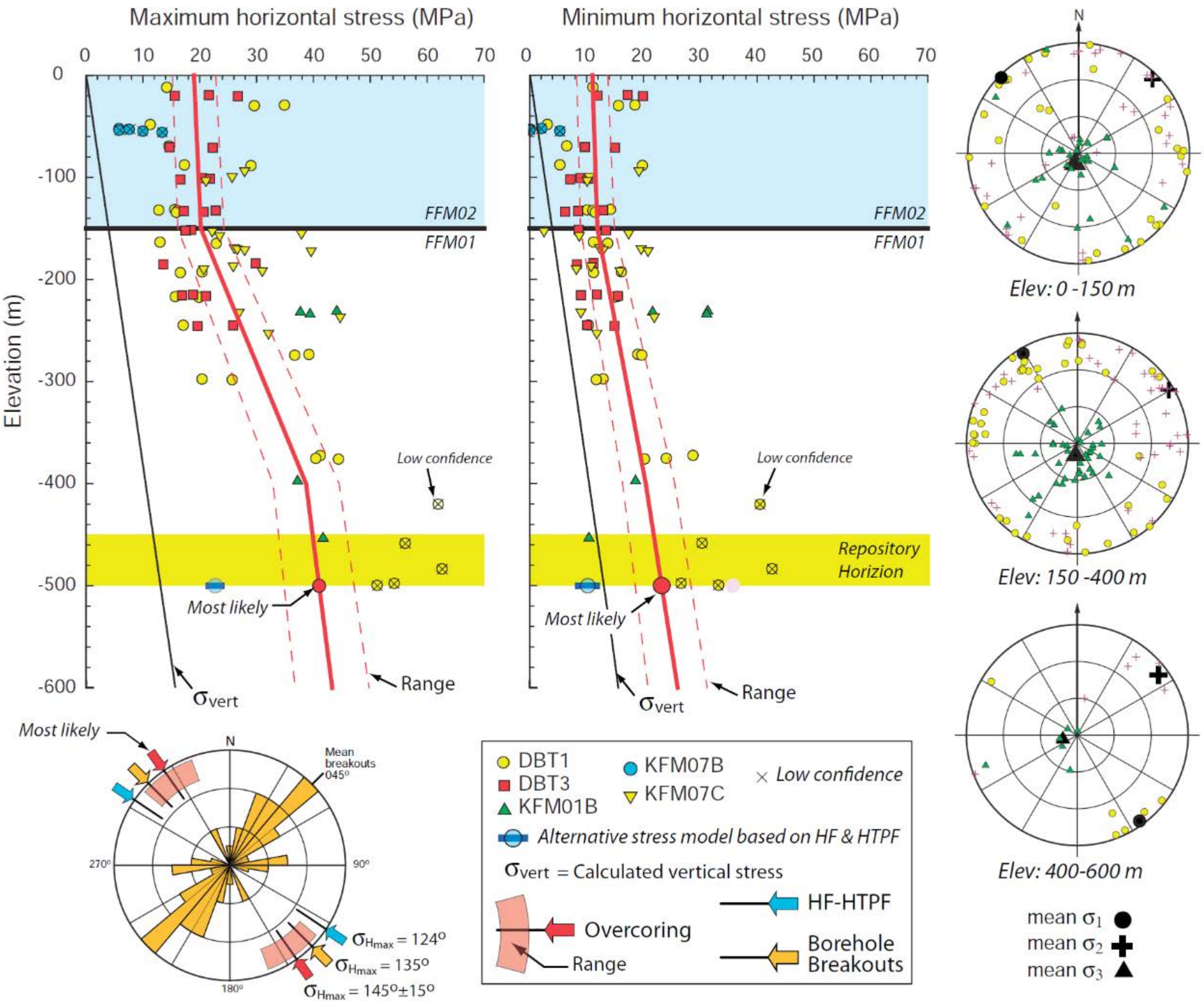


Figure 19. Evaluation of in-situ state of stress at Forsmark based on overcoring data and indirect observations of borehole breakouts and core disking (red and yellow data points). An alternative stress model based on hydraulic fracturing and HTPF data is also presented (blue data points). After SKB, 2008.

Table 9. Comparison of intact rock properties.

Property	Olkiluoto	Forsmark	Implications
Young's modulus	63 GPa	76 GPa mean value (69–83 GPa) min–max	Slightly stiffer rock at Forsmark; may support stress build-up vs. weaker surrounding rocks.
Uniaxial compressive strength, UCS	115 MPa	226 MPa (157–289 MPa)	Forsmark rock is stronger on average
Poisson´s ratio	0.25	0.23 (0.14–0.30)	
Uniaxial compressive strength. Peak value	115 MPa	226 MPa (157–289 MPa)	Almost double strength for Forsmark intact rock
Crack initiation stress	52 MPa	116 MPa (60–189 MPa)	More than double for Forsmark intact rock
Cohesion Mohr-Coulomb	12.1 MPa	28 MPa	
Friction angle Mohr- Coulomb	53 degrees	60 degrees	
Indirect tensile strength, Brazilian test	13 MPa (10–17 MPa) Fig. 5-13 in OSD 2008	13 MPa (10–18 MPa)	Same values for both sites.
Direct tensile strength	7.9 MPa	11.1 MPa (7.9–13.2) Glamheden et al. 2007	Lower than indirect tensile strength by Brazilian test
Ratio of maximum stress to UCS at 400 m depth	22 %	8 % (Hydraulic methods) 17 % (Overcoring)	Conditions more likely to produce spalling at Olkiluoto.

mum horizontal stress changes abruptly from N-S to E-W as depth increases past the 300 m level. The regional direction of σ_H around Olkiluoto is at S34E (146º), which lies between these directions. The local direction of maximum stress for both Forsmark stress models is similar, and close to the regional direction NW-SE.

The apparent discontinuity at Olkiluoto requires a zone of weakness around 300 m depth. A correlation with the gently dipping deformation zone R20 is suggested on p. 159 of Posiva Report 2009-01. For Forsmark, a minor rotation of principal stresses across the gently dipping deformation zones ZFMA2 and ZFMF1 at a similar depth is suggested by 3-D numerical modeling (SDM-Site, p. 223–224). Both sites are considered to have fairly uniform stress fields below these features, through proposed repository depths of 400–500 m.

Before ending the site investigations at Forsmark, SKB made the decision to stop stress measurements in the deep boreholes because of the ring-core disking from overcoring measurements at depth below ca 200 m and the tendency to generate horizontal fractures from hydraulic fracturing. Instead SKB has decided to resolve the stress field and establish the stress model at the proposed repository site with rock mass overcoring around the periphery of the access tunnel in conjunction with construction of the tunnel.

Recently, Posiva has developed a rock mass overcoring stress measurement method whereby several large-diameter overcorings are made around the periphery of a tunnel or shaft from which the rock mass stress state at tunnel scale is determined. A compilation of old stress measurement results and data obtained from the new method is expected to be presented in the forthcoming site description OSD 2011. The comparison of stresses between the two sites presented in this report is based on data in OSD 2009 (Posiva 2009a).

6.2 Properties of intact rock

The intact rock properties refer to the visually unfractured rock and are determined from core samples selected from the diamond-drilled cores. The cores are prepared for testing in a rock mechanics loading equipment. The sample preparation and testing procedure for uniaxial and triaxial compression testing follows the ISRM Suggested Methods (Ulusay and Hudson, 2011). The stress – strain curve from testing is used to define the parameter values. Strength and deformability of intact rock are used for the design of the underground openings and for predicting the long-term safety.

The data presented in Table 9 are valid for the migmatitic gneisses (MIGN, GN) at Olkiluoto and are extracted mainly from OSD 2008. For Forsmark the data about the most dominant rock metamorphic granite to granodiorite belonging to fracture domain FFM01 are presented, SKB 2009a.

Table 10. Fracture mechanical properties

Property	Olkiluoto	Forsmark	Implications
Fracture friction angles	30 degrees	37 degrees (29–42, min–max)	Similar ranges for both sites.
Fracture cohesion values	0.48 MPa (0.39-0.62, min-max)	0.8 MPa (0.2–1.3, min-max)	Similar ranges for both sites.
Fracture normal stiffness	4300 GPa/m for all four fracture sets (tests at 10.6 MPa normal stress)	159–1833 GPa/m (tests at 20–MPa normal stress)	The large discrepancy of normal stiffness might be due to testing error of Olkiluoto fractures.
Fracture shear stiffness	1.1 GPa/m for all fracture sets (tests at 10.6 MPa normal stress)	18–52 GPa/m (tests at 20 MPa normal stress)	

Rock at Forsmark is harder and more competent with almost double strength compared with Olkiluoto migmatitic gneiss. The crack initiation stress and the USC for Olkiluoto is about half the values of Forsmark rock. With the present knowledge about the stress field at the two sites the conditions for spalling is more likely for the Olkiluoto site.

The higher indirect tensile strength from Brazilian test is governed by the uneven stress distribution and mixed-mode fracturing as the fracture propagates across the disc sample, Lanaro and Stephansson (2009).

6.3 Fracture mechanical properties

Data on fracture mechanical properties has been gathered for each site, including a few direct shear tests on 50–92 mm scales (Table 10). The tests for Forsmark fractures are not entirely comparable to those for Olkiluoto fractures, as different levels of normal stress (10.6 MPa at Olkiluoto vs. 20 MPa at Forsmark) were used. Friction angles and cohesion values had similar ranges for both sites. The normal-stiffness values reported for Forsmark were generally lower than the value reported for Olkiluoto, but for shear stiffness the opposite result was obtained. For Forsmark it is reported that there are no clear trends of depth dependence in the results about fracture properties.

Despite testing of Olkiluoto fractures at half the normal stress magnitude compared to Forsmark the normal stiffness is more than double the maximum value recorded for Forsmark. Typical values of shear stiffness of fractures are about one tenth of the normal stiffness. This rule of thumb fits the data reported for Forsmark but shear stiffness data for Olkiluoto is far too low. This overview implies that the testing procedure and/or data evaluation of shear-box experiments conducted on Olkiluoto samples need to be revisited. So far Posiva has only presented a few test data about fracture stiffness and additional data are expected to be presented in OSD 2011. SKB reported problems with testing and evaluation of fracture stiffness during the first phase of the site investigations at Forsmark. The testing procedure was modified and evaluation adjusted for presentation in later phases of investigation.

6.4 Rock mass deformability and strength

Rock-mass deformability on scales of meters is likely to be only indirectly related to laboratory tests on fractures at relatively small scales, depending on the fracture network configuration (orientation and size distributions and termination characteristics) as well as the mechanical properties of intact bedrock. For Olkiluoto, an empirical approach based on GSI rock mass quality has been supplemented by P-wave tomography to yield estimates of the deformation modulus in the range 47–61 GPa (Table 11). A combination of a similar empirical approach and numerical stress-deformation modeling with distinct element method (3DEC) for Forsmark yields a corresponding range of 39–81 GPa for the main rock and fracture domains at proposed repository depth, with mean values of 69–70 GPa (Table 11). Thus rock mass deformability for Olkiluoto fall within the range predicted for Forsmark, but the Forsmark rock mass is predicted to have a wider range overall, and stiffer on average than even the high-stiffness end of the distribution for Olkiluoto.

The uniaxial compressive strengths for the rock mass at proposed repository depths at the two sites overlap in range, but Forsmark rocks on average are stronger than even the high-strength end of the distribution for Olkiluoto. The lower strength of the rock mass at Olkiluoto means that the ratio of maximum stress to rock mass strength is higher

Table 11. Comparison of rock mass deformability and strength.

Property	Olkiluoto	Forsmark	Implications
Rock mass deformation modulus	47, 56, 61 GPa for GSI value 71, 81, and 92, respectively.	70 GPa (39–79 GPa, min–max) Harmonized value from theoretical and empirical approach.	Slightly stiffer rock at Forsmark; may support stress build-up vs. weaker surrounding rocks.
Poisson's ratio	0.25 for all GSI values	0.24 (0.12–0.33, min–max) Harmonized value.	
Uniaxial compressive strength	23, 40, 74 MPa for GSI value 71, 81 and 92, respectively.	92 MPa (23–153 MPa, min–max) According to Hoek-Brown failure criteria	As for intact rock, the rock mass at Forsmark is twice as strong as Olkiluoto
Friction angle Mohr-Coulomb	49, 50, 50 degrees for GSI value 71, 81 and 92, respectively.	51 degrees (32–56 degrees, min–max)	Similar for the two sites
Cohesion Mohr-Coulomb	4.1, 6.8 and 12.8 MPa for GSI value 71, 81 and 92, respectively.	24 MPa (6–42 MPa, min–max)	
Tensile strength	1.4, 2.9, 6.6 MPa for GSI value 71, 81 and 92, respectively.	2.4 MPa (0.6–4.0 MPa, min–max)	
Ratio of maximum stress to UCS for rock mass at 400 m depth	110 % for GSI 71 64 % for GSI 81 35 % for GSI 92	17 % Overcoring method 8 % Hydraulic methods	Conditions more likely to produce spalling at Olkiluoto.

for Olkiluoto (110, 64, and 35% at 400 m depth) than for Forsmark (17% to 8%, depending on which stress model is used). This ratio has implications for bedrock stability, as discussed in Section 6.6.

6.5 Properties of brittle deformation zones

Mechanical properties of brittle deformation zones have been estimated for ten zones at Olkiluoto, and three zones at Forsmark, mainly based on empirical approaches. For Olkiluoto, these properties are presented in terms of a deformation moduli (E =11–47 GPa) and compressive strengths (1–4 MPa) (p. 199, Posiva R 2009-01). For Forsmark these properties are presented in terms of normal stiffness (79–85 GPa/m) and shear stiffness (14–24 GPa/m) along with cohesion value (0.7 MPa) and friction angle (36 degrees), which could be used in a model that represents these brittle zones as equivalent fractures (Forsmark SDM-Site, p. 222). Comparison of these properties is not straightforward as it depends on the thicknesses of individual brittle deformation zones.

For both sites, the mechanical properties of brittle deformation zones are perhaps best regarded as properties to be calibrated based on an integrated model for the state of stress, with these estimates used to constrain the calibration. For both sites, uncertainties will be large due to the large scatter in *in-situ* stress measurement results.

6.6 Bedrock stability

The higher ratio of rock stresses to rock strength at Olkiluoto implies somewhat higher risk of bedrock instability at proposed repository depths, than for Forsmark. However the state of stress at depth at Forsmark is still poorly characterized due to measurement difficulties.

Fälth and Hökmark (2011) and Fälth et al (2010) have modeled the effect of end-glacial earthquakes on target fractures in the proposed repositories for the Olkiluoto and Forsmark sites, respectively using the three-dimensional distinct element code 3DEC. For the Olkiluoto model a target fracture with radius 75 m was used and the effect was analyzed for the distance of 100 m, 300 m and 500 m away from the primary deformation zone along which the rupture process is taking place during the earthquake. Three primary faults were selected, BFZ100 has a moment magnitude M_w=4.3 and is intersecting the repository and BFZ021 (M_w=5.8) and BFZ214 (M_w=5.9) located at the border of the Olkiluoto island. The sum of the present-day *in-situ* stresses from recent stress measurements at Olkiluoto and the glacially-induced stresses derived from Lund *et al*. (2009) was applied to the models. Constitutive models and parameter values for the rock mass, primary faults, target fractures are pore pressure are presented in Fälth and Hökmark (2011).

The comparison of the result of the modelling for Olkiluoto site analyzed with properties of the target fractures taken from Forsmark is presented in Figure 20. For all models analyzed the shear displacement is less than the critical shear displacement across a copper-steel canister to be used in a KBS-3V type of repository. The difference in shear displacements for the different faults at the two sites is due to differences in initial stresses where the relatively lower stresses at Olkiluoto play a role. In addition the application of larger seismic moments per unit fault area at Forsmark gives larger shear displacement. Other differences in the modelling that effect the final results are fault orientation and fault residual strengths where a small residual value was maintained in the Olkiluoto case. In the general conclusion of the comparison Fälth and Hökmark (2011) claim that the modelling conducted for the Olkiluoto site gives more realistic upper bound estimates of the seismic effect on Olkiluoto target fractures. The modelling approach and its results for Forsmark is more a worst case.

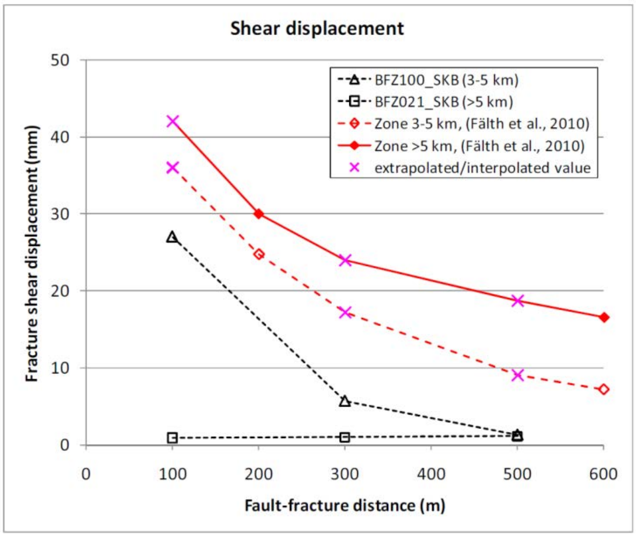


Figure 20. Comparison of fracture shear displacement of a target fracture in the proposed repository versus different distance from a major end-glacial earthquake. Data are presented for fracture zone BFZ100 intersecting the repository and BFZ021 at the westernmost end of Olkiluoto and two major deformation zones with the length 3–5 km and >5 km at the Forsmark site.

Lund *et al.* (2009) and Lund and Schmidt (2011) have conducted studies of stress evolution and fault stability at Forsmark and Olkiluoto during the Weichselian glaciation. They have modeled the glacially induced stress field using a three-dimensional, flat regional finite element model (Abaqus code) loaded by the ice sheet from the dynamic ice sheet model by SKB. The response of the models was compared to sea-level data and current day vertical and horizontal velocities from GPS data. At seismogenic depth of 9.5 km, the stress models show fault instability at both sites at the end of Weichselian deglaciation for a reverse background stress field, irrespective of the direction of the maximum and minimum horizontal stresses. With the assumption of a strike-slip background stress field the results varies more with the direction of the horizontal stresses. When using a local background stress model that considers the data from the stress measurements at the sites and best estimate of the stresses at large depths (reverse down to 1.7 km depth and strike-slip below 1.7 km) Olkiluoto and Forsmark remain stable during the entire glacial cycle. Also the results of the stress evolution modelling show that the stability field of the faults at 500 m depth is similar as for the seismogenic depth of 9.5 km.

7 Thermal properties

Thermal testing at Olkiluoto has focused mainly on veined gneiss as the most likely rock to be encountered around deposition holes in a repository. Among subordinate rock types, granite and pegmatite have higher thermal conductivity while granodiorite is the least conductive rock that has been tested. No data are available for tonalite. The thermal conductivity of veined gneiss is significant (about 3 W/m·K), with an anisotropy factor of 1.43 (higher thermal conductivity parallel to the schistosity than perpendicular to it). Structural anisotropy caused by migmatitic layering of micaceous and felsic rock types on scales of meters to tens of meters may increase the thermal anisotropy over larger scales. Anisotropy of subordinate rock types is generally less, so far as these have been evaluated. Measurements of thermal expansion and logging of *in-situ* temperature are so far missing for the Olkiluoto site.

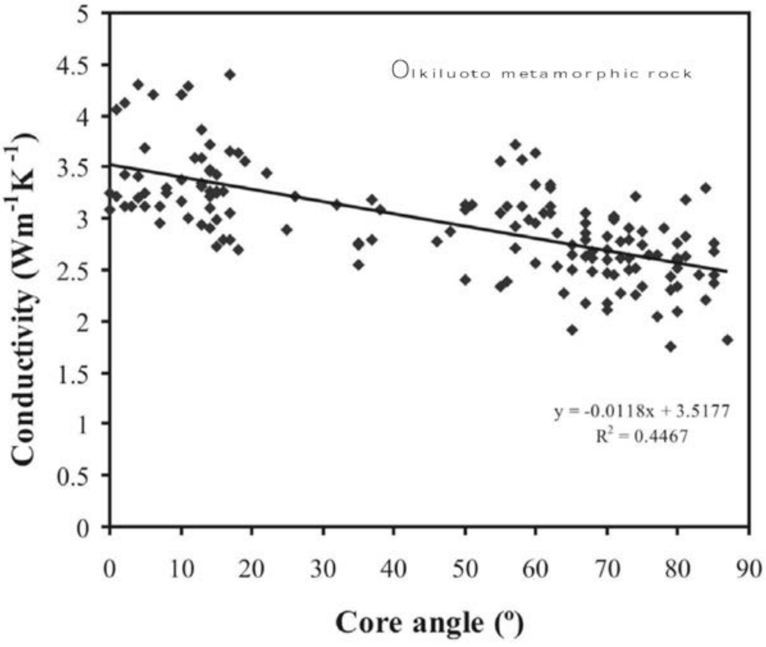


Figure 21. Thermal conductivity versus angle of schistosity of drill-core samples of Olkiluoto veined gneiss. An angle of 0° is along the schistosity and gives the highest conductivity. After Posiva (2009).

Thermal testing at Forsmark has focused on the major rock types in rock domains RFM029 and RFM045. The “granite to granodiorite” facies which is the dominant facies in RFM029 (74%) and a secondary facies in RFM045 (18%) has a 22% higher thermal conductivity (3.7 W/m·K) relative to Olkiluoto veined gneiss. Aplitic granite, which is a minor facies (1%) in RFM029 but the main facies in RFM045 (49%), has a 27% higher thermal conductivity. Two minor facies at Forsmark (”pegmatite and pegmatitic granite,” and “granite, granodiorite and tonalite”) have thermal conductivities similar to or slightly lower than Olkiluoto veined gneiss. One minor facies (amphibolite, at 4–6%) has a much lower thermal conductivity. The arithmetic mean of thermal expansion of the granite to granodiorite rocks in the temperature interval 20–80 C° is 7.7 10^{-6}. The *in-situ* temperature at proposed repository depths has been logged in six of the deep boreholes at Forsmark; the average temperature is ca 10 C°.

For Forsmark, numerical upscaling has been done with a geostatistical (Markov process) facies model. This yields (for a 5 m scale) thermal conductivities of around 3.6 W/m·K for both of the main rock units at proposed repository depth, about 20% higher than for Olkiluoto veined gneiss. Thermal anisotropy with higher thermal conductivity parallel to the foliation has also been recognized for the dominant granite to granodiorite facies at Forsmark, but the anisotropy factor is only about 1.15, so less significant than for Olkiluoto.

Heat capacities and coefficients of thermal expansion are similar between the two sites.

8 Comparative site understanding

8.1 Status of models

8.1.1 Hydrogeological models

Hydrogeological models of the Forsmark and Olkiluoto sites are at similar stages of development, and indeed, overlap considerably in terms of software, techniques, and modeling experts. At both sites, the basic approach is to describe the hydrogeological zones (HZs) and the remainder of the rock (fractured "rock mass") as separate entities. For Forsmark, the properties of the HZs are considered to vary with depth and (in some variants) along strike. For Olkiluoto uniform properties have been assigned to the HZs at least as initial values (Vaittinen *et al.*, 2009, p. 139); heterogeneity has been included in a few sensitivity cases of the numerical modeling by a geostatistical method of interpolation between borehole-HZ intersections where point estimates of HZ transmissivity are available (Löfman *et al.*, 2009, p. 25–26 and Appendix A).

For Olkiluoto, more reliance has been placed on an explicit equivalent-continuum description which is built up from block-scale hydraulic conductivities that are calculated from a hydrogeological DFN model (Hartley *et al.*, 2009). For Forsmark, this has been done implicitly in a model that includes both the HZs and rock mass. The latter approach gives more seamless coupling between scales, but at the cost of some transparency regarding the effective hydrogeologic properties of the rock mass. For both sites, the details of surface hydrology have been modeled using separate numerical models which use a simplified representation of the bedrock.

The hydrogeological models for both sites have been calibrated with respect to the single-hole hydrologic data and pumping tests with multiple observation holes (and multiple observation intervals in some of the holes). For both sites, the inability to match all observations is reasonable given that some aspects of heterogeneity are treated stochastically (namely, rock mass fracturing and, for Forsmark, variability of transmissivity within deformation zones). However, in neither case have the proponents yet demonstrated that the variability in residual errors is consistent with the stochastic representation.

Both sites have been modeled using a coupled density-dependent flow and transport model for salinity (or TDS). This yields predictions of salinity profiles along drillholes (as well as several other constituents representing reference water components in the case of Forsmark – Cl, Br, $\delta^{18}O$, and HCO_3), which have been used for further tuning of the model parameters, particularly diffusion porosities. The data for making this comparison are sparse (particularly for Forsmark), and the results appear to be sensitive to the initial conditions that are chosen for simulations of the most recent glacial and current interglacial periods. For both sites, the overall patterns have been matched to a reasonable degree, but for a few boreholes the observed depths of interfaces between waters of contrasting salinity differ from predictions by 200 m or more (as detailed in Section 4.6).

Hydrologic monitoring data are being collected from the completed drillholes, but so far these have not been used to evaluate responses of the models to natural diurnal or seasonal fluctuations in the surface boundary conditions. In the case of Olkiluoto, drawdowns and inflows to the ONKALO have been modeled; this provides a test of the hydrogeological model's ability to predict flows under significantly altered hydraulic gradients.

Key uncertainties in the hydrogeological models for both sites include:

- Heterogeneity of HZ transmissivities and whether these tend to decrease with depth (as assumed at Forsmark but not at Olkiluoto, though the evidence for the two sites is similar);

- Completeness of the identified set of HZs, both within these sites, and in adjoining seabed areas where data are more limited and/or of lower resolution;
- Frequency, connectivity, and transmissivities of conductive features in the size range from 10 m to 1000 m, including extensive single fractures and minor deformation zones;
- General uncertainty in whether the Hydro-DFN models, based mainly on sparse borehole and outcrop data (plus tunnel data from shallow depths at Olkiluoto), accurately reflect the rock in the target volumes at these sites; and
- Sensitivity of calibration of density-dependent flow models to assumptions regarding initial conditions and homogeneity of parameters governing diffusion/dispersion of salinity.

These uncertainties are likely to persist in large degree even with additional data from underground construction.

8.1.2 Hydrogeochemical models

A SDM and interpretation for Olkiluoto was reported by Posiva in a 'baseline hydrogeochemistry' report in 2004. Evolution of the major cation concentrations and also of pH and alkalinity is interpreted in terms of mixing of end-member groundwaters with water-rock reaction (including cation exchange). The proposed model for redox-active solutes, sulphate and iron, involves sulphate reduction possibly associated with methane oxidation in the transition zone between Littorina-derived brackish groundwater and deeper saline groundwaters. Groundwater in the present-day system at Olkiluoto is interpreted to be predominantly from glacial/postglacial water sources down to about 350 m; below that there is greater uncertainty about water sources and ages, and the minor proportions of postglacial water. Target depth for the proposed repository is in this depth range, and thus hydrochemistry and isotope hydrology are not directly quantitative for the SDM.

The SDM for hydrogeochemistry that is reported in Olkiluoto Site Description 2008 follows the earlier baseline description but is more substantial because of the weight of evidence provided by added data and more extensive interpretation and modelling. In addition to data from additional surface-based boreholes and long-term monitoring installations, including attempts to target low transmissivity rock and to correlate water samples with specific hydrogeological zones, there are also hydrochemical data for matrix pore waters. There has also been a new strand of palaeohydrogeological modelling that uses hydrochemistry data, namely TDS or Cl^- concentrations to calibrate hydrogeological and transport parameters and thus to assess performance of the flow-transport model. This calibration has so far been iterated twice, in 2006 and 2008. However it has limited scope because it has simulated salinity evolution only from 4800 y ago (post-Littorina base case) and from 10000 y ago (post-glacial variant). There has been no attempt to include the effect of glacial meltwater intrusion in the model.

Hydrogeochemical interpretation and SDM development for Forsmark have been based on a similar range of data sources and models up to the reporting of SDM-Site in 2008. In this case, the SDM can be considered to be presented with a greater degree of confidence. This derives from quality control on key data such as Eh, the development of mixing modelling using SKB's 'M3' code, the greater amount of pore water data (though interpretation is still complex and uncertain), and the more advanced development of palaeohydrogeological modelling using the CONNECTFLOW code (which has similarly simulated only post-glacial hydrogeological and hydrochemical evolution). Nevertheless, the general status of the conceptual modelling in the SDM is rather similar as for Olkiluoto. The present-day groundwater system at Forsmark is understood to have different degrees of mixing of Littorina water, glacial water and deep bedrock saline water. But the quantitative implications for the key groundwater movements and solute transport processes have not been clarified for either site. Another key aspect of hydrogeochemical interpretation and modelling also remains incomplete in both cases – water-rock reaction modelling to understand the evolution of major cations in the mixed groundwaters is an open issue that is relevant to the safety case model for geochemical evolution of the buffer.

8.1.3 Thermomechanical models

Models for rock stress are at a higher level of sophistication for Forsmark, in that numerical models accounting for the planes of weakness along deformation zones have been presented which help to illustrate the interpretation of stresses as a function of both depth and lateral position at the site. However, uncertainties regarding the interpretation of *in-situ* stress measurements leave doubts regarding even the most fundamental results of these stress models.

The simpler model presented for Olkiluoto (piecewise linear fits to the principal stress components with depth) benefits from the support of a more consistent set of *in-situ* stress measurements, plus additional measurement techniques (Kaiser Effect, shaft convergence, large-scale overcoring). However, the inferred rotation of the directions of maximum and minimum horizontal stresses at 300 m depth is assumed to be related to the shallow-dipping deformation zone R20. A numerical model may be needed to show how this interpretation can be justified.

Rock deformability and strength of the rock mass for Forsmark has been determined with a theoretical approach using DFN models for fracture generation in combination with 3DEC distinct element modelling. The uncertainty of geology DFN at proposed repository depths causes uncertainties in determination of the so-called theoretical strength and deformability data extracted from the modelling results. The uncertainty is propagating once SKB is combining the theoretical results with an empirical approach using classification systems. For Olkiluoto the rock mass deformability and strength is based on the intact rock strength and the rock mass quality from Q´and GSI values from tunnel mapping. For both sites the calculated values of strength and deformability belong to the empirical rock mass quality classes good, very good and extremely good. The ability to map the rock mass quality in the tunnel at Olkiluoto gives a higher confidence of the presented results from the two sites.

The thermal properties model for Forsmark is well-developed, making use of a geostatistical facies modeling approach to derive upscaled values of thermal properties from core-sample-scale measurements combined with data on facies transition probabilities. A comparable rationale for upscaling thermal properties is needed for Olkiluoto, particularly to check the possibility that structural anisotropy on scales of meters to tens of meters may accentuate the strong thermal anisotropy that has been already been measured on the core-sample scale. Posiva has developed a logging tool for determination of *in-situ* thermal properties. The tool has been applied in some of the deep boreholes at Olkiluoto. There is still a need for such a logging tool for *in-situ* measurements in boreholes during the construction phase of the proposed repository.

The strength and deformability of the major and intermediate deformation zones in Forsmark and the brittle deformation zones at Olkiluoto are difficult to characterize from borehole observations from the surface. SKB and Posiva need to take a broadly bounded approach to sensitivity analyses of the parameters, factors and constants included in the analytical expressions (Mohr-Coulomb and Hoek and Brown failure criteria) and empirical relations (Q, RMR and GSI system) for strength and deformability.

8.2 Key differences affecting safety functions

Key differences between the sites that affect safety functions are listed here in three main groups: hydrogeochemistry, hydrogeology, and rock mechanics.

Six hydrogeochemical topics from this comparison have been identified in this review as showing differences between the sites that potentially could affect safety functions. These are:

- Redox and biogeochemistry at proposed repository depths;
- Salinity at and below proposed repository depths;
- Palaeohydrogeology of sub-glacial and Littorina waters;
- Cation hydrogeochemistry and water-rock reaction;
- Pore water compositions in rock matrix and hydrogeological implications;
- Rock fabric, secondary minerals and retention model.

In addition, the following five hydrogeological topics have been identified as potentially significant for safety functions:

- Brittle deformation fabric differences on multiple scales that affect vertical hydraulic conductivity;
- Differences in apparent frequency of encountering water-conducting networks at proposed repository depths;
- Shallow bedrock hydraulic properties;
- Unique intrusive or dissolution features;
- Connectivity of site-scale models to regional-scale features.

Finally, the following three topics related to general geology and rock mechanics are highlighted as of possible importance:

- Mesoproterozoic rocks in vicinity and possibilities for human-intrusion scenarios;
- Rock stresses and bedrock stability at proposed repository depths;
- Thermal anisotropy.

These issues are all regarded as potentially significant to safety functions. The ordering below is purely in terms of geoscientific discipline and is not suggested as representing the relative importance of these issues for repository safety, recognizing that repository safety hinges upon multiple barrier functions.

8.2.1 Redox and biogeochemistry at proposed repository depths

There are greater uncertainties in the range of Eh in groundwaters at proposed repository depths at Olkiluoto, due to poor data, than at Forsmark. In the latter case, data point to SO_4/HS and possibly CH_4/CO_2 controls on Eh as measured, whilst Fe^{II} minerals are the dominant long-term buffer on redox. There is a clear difference between dissolved methane concentrations in groundwaters at and below repository depth at the two sites. Below 300 m at Olkiluoto, methane increases with depth to about 1000 mL per litre whereas at Forsmark it remains very low, typically <0.10 mL per litre. The basic reason for this fundamental difference is not known, though a predominantly abiogenic source of methane, deep in the bedrock, is inferred at Olkiluoto. More significantly, anaerobic oxidation of methane by sulphate is inferred to account for their sharp concentration gradients just below 300 m. If this occurs, then it means that methane abundance is a significant factor in the production of sulphide which is the most significant corrodant with respect to copper.

8.2.2 Salinity at and below proposed repository depths

Large variations of salinity influence the rate of the electrochemical process of corrosion and also potentially affect the swelling pressure and stability of bentonite buffer. Whilst the salinities of groundwaters at repository depths at Olkiluoto and Forsmark are broadly similar, 5000–7000 mg/L Cl^-, there is a steeper gradient below repository depths at Olkiluoto. The highest observed salinities down to 1000 m, however, are not of direct concern but it can be argued that the occurrence and proximity of high salinity in deep bedrock at Olkiluoto presents a more significant uncertainty in the future evolution of this safety function.

8.2.3 Palaeohydrogeology of sub-glacial and Littorina waters

The interpretations of the maximum depths of penetration of glacial meltwater and Littorina water during post-glacial evolution of the two sites are different, though they are generalized interpretations. Inferred deeper penetration at Forsmark (>500 m) than at Olkiluoto (≤300 m) suggests that the large-scale vertical transmissivity at Forsmark is the greater. This goes counter to the hydrogeological interpretation that Forsmark has the ‘tighter’ hydrogeological properties but is consistent with some of the differences in structural geological and hydrogeological fabric that have been noted elsewhere in this report. Overall, this difference highlights a general lack of understanding and coherence between various lines of evidence for palaeohydrogeology and the site-scale groundwater systems.

8.2.4 Cation hydrogeochemistry and water-rock reaction

Brackish and saline waters at the two sites evolve towards Ca-(Na, Mg)-Cl-(SO_4) compositions in different ways with respect to total mineralisation. To a large extent, as interpreted for both SDMs, the overall evolution is dominated by mixing of distinct water sources. However a minor but potentially significant contribution to hydrochemical evolution is due to water-rock reaction. This shows particularly in the changing relative proportions of Ca, Na, Mg, Sr and K. In neither SDM is there a water-rock reaction model that interprets satisfactorily the mineral dissolution, precipitation and ion-exchange reactions. Sufficient understanding of these reactions is required to constrain future variations of cations at repository depth and potential effects on buffer evolution. Geochemical evolution of dilute glacial infiltration in terms of divalent: monovalent cation ratio ($[Ca^{2+}+Mg^{2+}]/Na^+$) is perhaps the most significant uncertainty with respect to the buffer safety function.

8.2.5 Pore water compositions in rock matrix and hydrogeological implications

Evidence from pore water analyses for Forsmark has been interpreted as indicating that pore water compositions and patterns with respect to fracture waters are indicative of palaeohydrogeology over very long periods (*i.e.* pre-glacial through to Holocene) and the small-scale hydrogeological properties between transmissive fractures and rock matrix. The pattern at Olkiluoto is more like the hanging wall rock domain at Forsmark, *i.e.* pore waters are much more dilute than fracture waters. It is thought that exchange affected pore water compositions more recently than in the tighter rock in the footwall domain at Forsmark. In general, though, the low level of understanding of pore water compositions and their variability at small and large scales is a challenge to the flow-transport modelling at both sites. Another aspect of this that is yet to be considered is the implication of contrasting salinities, and thus of water densities, in pore waters and fracture waters for the hydraulics of the flow-transport model.

8.2.6 Rock fabric, secondary minerals and retention model

There are some differences in the secondary mineral assemblages, and the general effects of past episodes of hydrothermal alteration on rock fabric at the two sites. However, it is unclear how much of these differences are due to different mineralogical and petrographic objectives, methods and detection capabilities, and how much is real. The retention models for the two sites are conceptually different, though it is not clear how these conceptual models and the different mineral and alteration fabrics in fractures and matrix are translated into specific localised retention modelling in radionuclide transport models.

8.2.7 Brittle deformation fabric differences on multiple scales that affect vertical hydraulic conductivity

The meso- to large-scale brittle deformation fabric at depth at Olkiluoto has a stronger horizontal to sub-horizontal component than that for Forsmark, both in terms of discrete fractures and, apparently, larger-scale brittle-deformation zones. The result is that the deeper bedrock at Forsmark (*i.e.*, below the uppermost 150 m which are characterized by sub-horizontal sheet jointing) is more favorable to vertical rather than horizontal groundwater flow, while the deeper bedrock at Olkiluoto is more favorable to horizontal rather than vertical flow.

8.2.8 Differences in apparent frequency of encountering water-conducting networks at depth

The frequency of Posiva Flow Log features, indicative of intersections with water-conducting fracture networks, is only about one per 250 m of drillhole at Forsmark vs. one per 50 m at Olkiluoto. This indicates that Forsmark is likely to contain larger volumes of rock that do not participate in such networks via high-conductivity connections. However, this very sparse but evidently connected fracture network also raises doubts about the underlying conceptual model of essentially random (Poisson-process) fractures.

8.2.9 Shallow bedrock hydraulic properties

The extremely high horizontal transmissivity of the uppermost 150 m of bedrock at Forsmark, due to horizontally persistent fractures with high transmissivity, is a clear difference with respect to Olkiluoto, for which data are on the upper bedrock are limited but indicate a less strong contrast with the deeper bedrock. At Forsmark, the shallow, highly transmissive zone appears to short-circuit flows driven by topographic contrasts within the site, resulting in an extremely flat groundwater table. In contrast, the water table at Olkiluoto is strongly correlated to topography. This implies a stronger impact of surface topography at depth, possibly including topographically-driven groundwater recharge-discharge cells that could play a role in radionuclide transport.

8.2.10Unique intrusive or dissolution features

Each site contains unique features that could play a role in groundwater flow and radionuclide transport. At Olkiluoto, diabase dykes are found which could act as transmissive features if they are more highly fractured than the surrounding bedrock. This has been observed with diabase (dolerite) dykes of similar age at the Laxemar site in Sweden. At Forsmark, the so-called "porous granite" zones, formed by hydrothermal dissolution of quartz, is found in at least small parts of the site, with extremely high hydraulic conductivities. The extent of these "porous-granite" zones is still poorly understood and is not well discussed in SDM-Site.

8.2.11 Connectivity of site-scale models to regional-scale features

At both sites, connectivity of the local models to regional-scale boundary conditions appears to be restricted by a dearth of deformation zones in areas that are presently below sea level. No geological explanation has been presented that accounts for this difference, so the possibility must be considered that it is simply an artifact of reduced resolution for data sets that were used to deduce seabed lineaments. The effect appears to be worse for Olkiluoto than for Forsmark. The consequence is that coupling to the boundaries of the hydrogeological model domains may be weaker in the models than in nature, resulting in an underestimation of regional flow components through the repository target volumes, both for present and future climates.

8.2.12 Mesoproterozoic rocks in vicinity and possibilities for human-intrusion scenarios

Olkiluoto differs from Forsmark in terms of proximity to Mesoproterozoic rapakivi granites and sandstones. Conceivably these might be targets for future exploitation, as relatively unique rocks for the Fennoscandian region (e.g. rapakivi granites have been quarried elsewhere as decorative building stones). Conversely, Forsmark lies at the edge of a mining district formed by secondary mineralization, and some metavolcanic rocks currently offshore bear superficial resemblance to ore bodies that have been mined in recent centuries. Thus both sites are in the vicinity of geological formations that might conceivably be exploited or at least explored in the future (though neither site is indicated to contain such formations within its boundaries).

8.2.13 Rock stresses and bedrock stability at proposed repository depths

The ratio of maximum principal stress to rock strength is significantly higher at Olkiluoto than at Forsmark. While both sites may be at some risk of spalling around deposition holes, particularly if the higher-stress interpretation of Forsmark is believed, Olkiluoto appears to have less of a safety factor for avoiding this phenomenon. Consequences of spalling range from enhanced flow and transport around deposition holes, to a need to abandon some deposition holes if the failure is noticed before canister emplacement. Failure in repository tunnels is also a possibility; this could lead to instability and rock spalling during construction and also lead to additional pathways for flow and transport along the tunnels if backfill swelling pressure is not sufficient to prevent such failures.

Posiva and SKB have performed dynamic modelling of the effect of large magnitude earthquakes along major faults on target fractures at different distance from the epicenter to the fracture in the proposed repository. The model output is presented as shear displacement along the target fracture for different distance from the earthquake fault. The calculated shear displacement for the two sites is calculated to be less than the limit shear displacement for the steel-copper canister. The more realistic input data to the modelling like stress data, fault orientation and fault residual strength for the Olkiluoto site resulted in less shear displacement compared with Forsmark.

8.2.14 Thermal anisotropy of host rock

The rock at Olkiluoto has significantly higher thermal conductivity parallel to the gneissic foliation, than perpendicular. Forsmark also shows anisotropy related to foliation, but this is much weaker. The anisotropy for Olkiluoto may be accentuated at larger scales due to larger-scale rock fabric. This anisotropy implies a directional dependence for minimal canister spacing (allowing for heat dissipation), and thus may affect layout of a repository and possibly the maximum number of canisters that can be emplaced for a given repository footprint.

9 Conclusions

The Olkiluoto and Forsmark sites share broadly similar regional settings and geologic histories. There are remarkable similarities in terms of hydrogeochemistry and hydrogeology, despite differences in lithology, rock strength and patterns of brittle deformation. These similarities reflect the dominant influence of postglacial Littorina/Baltic water intrusion followed by subaerial exposure and coastal location at the Baltic Sea. Both sites also contain deep bedrock saline groundwater, though this is more evident at Olkiluoto than Forsmark.

Some differences are apparent that could potentially impact safety. The key differences, as discussed in Section 8, include:

- Redox controls, buffering and biogeochemistry at proposed repository depths;
- Salinity gradients at and below proposed repository depths;
- Methane concentrations at and below proposed repository depths;
- Depths to which glacial water and Littorina water penetrated;
- Cation hydrogeochemistry and water-rock reaction;
- Pore water compositions in rock matrix;
- Rock fabric, secondary minerals and alteration with respect to radionuclide retention.
- Brittle deformation fabric differences on multiple scales that affect vertical hydraulic conductivity;
- Differences in apparent frequency of encountering water-conducting networks at proposed repository depths;
- Shallow bedrock hydraulic properties;
- Unique intrusive or dissolution features;
- Connectivity of site-scale models to regional-scale features.
- Mesoproterozoic rocks in vicinity and possibilities for human-intrusion scenarios;
- Rock stresses and bedrock strength and deformability at proposed repository depths;
- Thermal anisotropy.

These differences are all potentially significant to safety functions, but none are so severe that their safety relevance would clearly have a direct, critical effect on performance assessment calculations. In general, the effects of these differences would need to be evaluated in terms of secondary processes that affect safety functions (for example, the impact of methane on the biogeochemical reduction of sulphate to sulphide, and thus on future scenarios for canister corrosion). Considering also that site safety is a composite of multiple barrier functions, the impact of these differences in terms of overall site suitability is difficult to judge without a full safety assessment for each site that includes an analysis of how these differences and associated uncertainties may influence safety.

However, given the results of the SR-Can safety assessment based on the KBS-3 disposal concept that is being proposed for both sites, the part of the safety functions assigned to the geosphere is mainly to provide a stable environment for the engineered barriers (waste package and buffer). Differences in redox and salinity at depth, are of prime importance, while vertical hydraulic conductivity is important for helping to maintain favorable conditions under changing surface conditions, for example circumstances that could lead to infiltration of very dilute glacial meltwaters.

10 References

Aaltonen, I., Lahti, M., Engström, J., Mattila, J., Paananen, M., Paulamäki, S., Gehör, S., Kärki, A., Ahokas, T., Torvela, T. and Front, K., 2010. Geological model of the Olkiluoto site, Version 2.0. Working Report 2010-70, Posiva Oy, Eurajoki.

Ask D., Cornet, F., Fontbonne, F., and Brunet, C., 2007. Stress measurements with hydraulic methods in boreholes KFM07A, KFM07C, KFM08A, KFM09A, and KFM09B. Forsmark site investigation. Progress Report P-07-206, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Banwart, S.A., 1999. Reduction of Fe(III) minerals by natural organic matter in groundwater. Geochimica et Cosmochimica Acta, vol. 63, p. 2919–2928.

Buoro, A., Dahlbo, K., Wiren, L., Holmén, J., Hermanson, J., and Fox, A. (editor), 2009. Geological discrete-fracture network model (version 1) for the Olkiluoto site, Finland. Posiva Working Report 2009-77, Posiva Oy, Eurajoki.

Drake, H., and Tullborg, E-L., 2006. Mineralogy and geochemistry of rocks and fracture fillings from Forsmark and Oskarshamn: Compilation of data for SR-Can. Report R-06-109, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Eichinger, F.L., Waber, H.N. and Smellie, J.A.T., 2006. Characterisation of matrix pore water at the Olkiluoto investigation site, Finland. Working Report 2006-103, Posiva Oy, Eurajoki.

Eichinger, F., Hämmerli, J., Waber, H.N., Diamond, L.W. and Smellie, J.A.T., 2010. Characterisation of matrix pore water and fluid inclusions in Olkiluoto bedrock from drilling OL-KR47. Working Report 2010-58. Posiva Oy, Eurajoki.

Fälth, B. and Hökmark, H., 2010. Effects of large earthquakes on a KBS-3 repository. Technical Report TR 08-11, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Fälth, B. and Hökmark, H., 2011. Modelling end-glacial earthquakes at Olkiluoto. Working Report 2011-13, Posiva Oy, Eurajoki.

Follin, S., Johansson, P-O., Hartley, L., Jackson, P., Roberts, D., and Marsic, N., 2007. Hydrogeological conceptual model development and numerical modelling using CONNECTFLOW, Forsmark modelling stage 2.2. Report R-07-49, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Follin, S., Stephens, M.B., Laaksoharju, M., Nilsson, A-C., Smellie, J.A.T. and Tullborg, E-L. 2008 Modelling the evolution of hydrochemical conditions in the Fennoscandian Shield during Holocene time using multidisciplinary information. Applied Geochemistry, vol. 23. no. 7, p. 2004–2020.

Fox, A., La Pointe, P., Hermanson, J., and Öhman, J., 2007. Statistical geological discrete fracture network model: Forsmark modelling stage 2.2. Report R-07-46, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Gimeno, M.J., Auqué, L.F., Gómez, J.B. and Acero, P., 2008. Water-rock interaction modeling and uncertainties of mixing modelling. SDM-Site Forsmark. Report R-08-86, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Goodman, R.E., 1963. Subaudible noise during compression of rocks, Geological Society of America Bulletin, vol. 74, p.487–490.

Glamheden, R., Fredriksson, A., Röshoff, K., Karlsson, J., Hakami, H., Christiansson, R., 2007. Report R-07-31, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Hallbeck, L. and Pedersen, K., 2008. Explorative analysis of microbes, colloids and gases. SDM-Site Forsmark. Report R-08-85. Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Hartley, L., Hoek, J., Swan, D., Roberts, D., Joyce, S., and Follin, S., 2009. Development of a hydrogeological discrete-fracture network model for the Olkiluoto site descriptive model 2008. Working Report 2009-61, Posiva Oy, Eurajoki.

Hirvonen, H. and Hatenpää, E., 2006. Analysis results of PAVE sampling of groundwaters from open boreholes OL-KR-10, OL-KR19, OL-KR29, OL-KR30, OL-KR32 and OL-KR35 at Olkiluoto, Eurajoki, in 2005. Working Report 2006-108, Posiva Oy, Eurajoki.

Järvinen, E., Manninen, P., Takala, M. and Vilhunen, S., 2011. Sampling and characterisation of groundwater colloids in Onkalo at Olkiluoto, Finland 2009–2010. Working Report 2011-29, Posiva Oy, Eurajoki.

Johansson P-O, 2008. Description of surface hydrology and near-surface hydrogeology. Site descriptive modelling, SDM-Site Forsmark. Report R-08-08, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Kalinowski, B.E. (ed.), 2008. Background complementary hydrogeochemical studies. SDM-Site Forsmark. Report R-08-87, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Karvonen, T. 2008. Surface and near-surface hydrological model of Olkiluoto Island. Working Report 2008-17, Posiva Oy, Eurajoki.

Korhonen, K., Kuivamäki, A., Paananen, M., and Paulamäki, S., 2005. Lineament interpretation of the Olkiluoto area. Working Report 2005-34, Posiva Oy, Eurajoki.

Laaksoharju, M., Smellie, J., Tullborg, E-L., Gimeno, M., Hallbeck, L., Molinero, J. and Waber, N., 2008a. Bedrock hydrogeochemistry Forsmark. Site Descriptive Modelling SDM-Site Forsmark. Report R-08-47, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Laaksoharju, M., Smellie, J, Tullborg, E-L., Gimeno, M., Molinero, J., Gurban, I. and Hallbeck, L., 2008b. Hydrogeochemical evaluation and modeling performed within the Swedish site investigation programme. Applied Geochemistry, v. 23, no. 7, p. 1761–1795.

Laaksoharju, M., Gascoyne, M. and Gurban, I., 2008c. Understanding groundwater chemistry using mixing models. Applied Geochemistry, V. 23, no. 7, p. 1921–1940.

Lahtinen, R., Korja, A., and Nironen, M., 2005. Paleoproterozoic tectonic evolution. In: Lehtinen, M., Nurmi, P., and Rämö, T. (Eds.), Precambrian Geology of Finland – Key to the Evolution of the Fennoscandian Shield, Developments in Precambrian Geology 14, p. 533–562, Elsevier, Amsterdam.

Lanaro, F., Sato, T., and Stephansson, O., 2009. Microcrack modelling of Brazilian tensile tests with the boundary element method. International Journal of Rock Mechanics and Mining Sciences, vol. 46, no. 3, p. 450–461.

Lehtonen, A., Cosgrove, J.W., Hudson, J.A., and Johansson, E., 2012. An examination of *in situ* rock stress estimation using the Kaiser effect. Engineering Geology vol. 124, p. 24–37.

Löfman, J., Mészáros, F., Keto, V., Pitkänen, P., and Ahokas, H., 2009. Modelling of groundwater flow and solute transport in Olkiluoto – Update 2008. Working Report 2009-78, Posiva Oy, Eurajoki.

Lund, B., Schmidt, P., and Hieronymus, C., 2009. Stress evolution and fault stability during the Weichselian glacial cycle. Report TR 09-15, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Lund, B. and Schmidt, P., 2011. Stress evolution and fault stability at Olkiluoto during the Weichselian glaciation. Working Report 2011-14, Posiva Oy, Eurajoki.

Luukkonen, A. 2006. Estimations of durability of fracture mineral buffers in the Olkiluoto bedrock. Working Report 2006-107, Posiva Oy, Eurajoki.

Martin, C.D., 2007. Quantifying in situ stress magnitudes and orientations for Forsmark. Forsmark stage 2.2. Report R-07-26, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Nykyri, M., Nordman, H., Marcos, N., Löfman, J., Poteri, A. and Hautojärvi. A., 2008. Radionuclide Release and Transport – RNT-2008. Report 2008-06, Posiva Oy, Eurajoki.

Paananen, M., and Kuivamäki, A., 2007. Regional lineament analysis of the southern Satakunta area. Working Report 2007-04, Posiva Oy, Eurajoki.

Paaso, N., Hatenpää, E. and Ylä-Mella, M., 2006. Groundwater sampling at Olkiluoto, Eurajoki, from the borehole OL-KR6 during a long-term pumping test in 2004. Working Report 2006-11, Posiva Oy, Eurajoki.

Penttinen, T., Partamies, S., Lahdenperä, A-M., Pitkänen, P., Ahokas, T. and Kasa, S., 2011. Results of monitoring at Olkiluoto in 2009, hydrogeochemistry. Working Report 2010-44. Posiva Oy, Eurajoki.

Pitkänen, P., Partamies, S. and Luukkonen, A., 2004. Hydrogeochemical interpretation of baseline groundwater conditions at the Olkiluoto site. Posiva 2003-07. Posiva Oy, Eurajoki.

Posiva, 2009a. Olkiluoto Site Description 2008, Part 1. Report 2009-01, Posiva Oy, Eurajoki.

Posiva, 2009b. Olkiluoto Site Description 2008, Part 2. Report 2009-01, Posiva Oy, Eurajoki.

Rämö, O.T. and Haapala, I., 2005. Rapakivi granites. In: Lehtinen, M., Nurmi, P., and Rämö, T. (eds.), Precambrian Geology of Finland – Key to the Evolution of the Fennoscandian Shield, Developments in Precambrian Geology 14, p. 533–562, Elsevier, Amsterdam.

Sahlstedt, E., Karhu, J. and Rinne, K., 2009. Paleohydrogeological Implications from Fracture Calcites and Sulfides in a Major Hydrogeological Zone HZ19 at Olkiluoto. Working Report 2009-54. Posiva Oy, Eurajoki.

Sandström, B., Tullborg, E-L., Smellie, J., MacKenzie, A.B. and Sksi, J., 2008. Fracture Mineralogy of the Forsmark Site. SDM-Site Forsmark. Report R-08-102, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Sandström, B. and Stephens, M.B., 2009. Mineralogy, geochemistry, porosity and redox properties of rocks from Forsmark. Compilation of data from the regional model volume for SR-Site. Report R-09-51, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB, 2006. Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. Main report of the SR-Can safety assessment. Technical Report TR-06-09, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB, 2008. Site description of Forsmark at completion of the site investigation phase. Technical Report TR-08-05, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB, 2010a. FEP Report for the safety assessment SR-Site. SKB Technical Report TR-10-45, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB, 2010b. Geosphere process report for the safety assessment SR-Site. Technical Report TR-10-48, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB 2010c, Data report for the safety assessment SR-Site. Technical Report TR-10-52, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

SKB, 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. Technical Report TR-11-01, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Smellie, J., Tullborg, E-L., Nilsson, A-C., Sandström, B., Waber, N., Gimeno, M. and Gascoyne, M., 2008. Explorative analysis of major components and isotopes. SDM-Site Forsmark. Report R-08-84, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Söderlund, P., Hermansson, T., Page, L.M., Stephens, M.B. 2008. Biotite and muscovite Ar^{40} – Ar^{39} geochronological constraints on the post-Svecofennian tectonothermal evolution, Forsmark site, central Sweden. International Journal of Earth Sciences vol. 98, no. 8, p. 1835–1851.

Streckeisen, A., 1974. Classification and nomenclature of plutonic rocks. Recommendations of the IUGS Subcommission on the Systematics of Igneous Rocks. Geologische Rundsch au, vol. 63, p. 773–786 .

Streckeisen, A., 1974, Classification and nomenclature of plutonic rocks: Recommendations of the IUGS Subcommission on the Systematics of Igneous Rocks. Geologische Rundschau Internationale Zeitschrift für Geologie, Stuttgart, v. 63, p. 773–785.

Tirén S.A. and Beckholmen, M., 2009. Displacement along extensive deformation zones at the two SKB sites: Forsmark and Laxemar. Unpublished report for Swedish Radiation Safety Authority, Stockholm, Sweden.

Tröjborn, M., Söderbäck, B. and Johansson, P-O., 2007. Hydrochemistry in surface water and shallow groundwater. Site Descriptive Modelling. SDM-Site Forsmark. Report R-7-55, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Tuominen, V., Hellä, P., and Vaittinen, T., 2006. Statistical model of fractures based on data from OL-TK7, OL-TK11, OL-KR24, OL-PH1 and ONKALO PL0 m – PL140 m. Working Report 2006-22, Posiva Oy, Eurajoki.

Ulusay, R., and Hudson, J. A., 2007. The complete ISRM suggested methods for characterization, testing and monitoring: 1974–2006. ISRM Turkish National Group of International Society for Rock Mechanics, Ankara, Turkey.

Vaittinen, T., Ahokas, H., and Nummela, J., 2009. Hydrogeological structure model of the Olkiluoto site – Update in 2008. Working Report 2009-15, Posiva Oy, Eurajoki.

Waber, H.N., Gimmi, T. and Smellie, J.A.T., 2009. Porewater in the rock matrix. Site descriptive modelling. SDM-Site Forsmark. Report R-08-105, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.