Olkiluoto Site Description
2008
Part 2

Posiva Oy

April 2009
Olkiluoto Site Description
2008
Part 2

Posiva Oy

April 2009

Base maps: © National Land Survey, permission 41/MML/09
8 TRANSPORT PROPERTIES

8.1 Objectives and applied approaches

The simulation of the transport properties supports both the assessment of radionuclide migration and the assessment of the evolution of the groundwater chemistry in the repository near-field. The migration of radionuclides is assessed in a separate analysis, based on the transport properties along the flow channels. The aim of this simulation is to identify the properties of the flow field that are important for geosphere retention, to characterise the release paths and to derive geosphere performance measures. Information on the potential flow paths can also be used to describe the overall flow conditions and potential discharge areas at the surface, that may be of interest in the performance assessment and in other parts of the safety case.

The main retention processes that are considered in this analysis are matrix diffusion and sorption. Geosphere performance measures that are important for these retention processes are the distribution of flow (WL/Q) and the rock matrix retention properties along the flow paths (porosity, diffusivity and $K_d$).

In fractured rocks, flow is usually very unevenly distributed between the different hydraulic features, leading to the development of preferential flow paths and channelled solute transport at all scales. The modelling approach is to take into account explicitly these hydraulic features at different scales and to apply an appropriate spatial resolution in the different sub-domains of the model. The applied modelling concept is based on a site-scale hydro-DFN model, that is composed of hydraulic structures at the regional scale, the site scale and the fracture scale. The site-scale Olkiluoto Hydro-DFN model is presented in Section 6.6 of this report.

The heterogeneity of the rock matrix retention properties is taken into account by applying generalised retention models to describe the structures of the immobile pore spaces (referred as immobile zones below). The approach is based on a simplification of the immobile pore spaces by making use of a small number of representative patterns of the different immobile zones. These immobile zones are represented by layers of pore space of constant thickness in the rock matrix adjacent to the fracture. The identification and specification of these immobile zones in the rock matrix is based on geological information, using drillhole core samples from different hydraulic features.

All transport simulations are calculated for steady state flow conditions, using the site-scale Hydro-DFN model. The flow paths for each simulation period are sampled by particle tracking in the DFN model. In principle, the varying sorption properties in space or time can be taken into account when the flow path information is applied in the radionuclide migration analysis. Presently, this option is restricted by the limited site-specific data currently available.

8.2 Data Evaluation

8.2.1 Immobile zones

The immobile zones in the rock encompass pore spaces in the rock mass that are saturated with water, but are not subject to flow. These immobile zones are important...
when making assessments of the migration of the radionuclides, because they are available for matrix diffusion and for the subsequent retention of solutes.

The identification and quantification of these immobile zones is based on the investigation of rock matrix properties from drill core samples adjacent to water-conducting fractures. A sufficient number of core samples has to be studied in order to establish a comprehensive site-scale view on the different types of water-conducting fracture and the immobile zones that are associated with them. These data are then used to conceptualise the water-conducting fractures, by using a small number of simplified retention models, that describe and quantify the pattern of the immobile zones in the different water-conducting fractures in the site-scale Hydro-DFN model (Poteri 2007).

Simplified retention models will conceptualise the immobile zones in the major (MHZ) and local (LHZ) hydrogeological zones and water-conducting fractures of the sparsely fractured background rock. It is likely that the retention models for the LHZs and MHZs are more heterogeneous, and include more and different immobile zones, than the retention models of the stochastic background fractures. Modelling exercises carried out, for example in the Åspö Hard Rock Laboratory, have shown that fracture filling materials and fracture coatings become saturated for the majority of the radionuclides under typical post-closure flow conditions. However, the aim of the conceptualised retention models is to directly represent the in situ heterogeneity in the transport model. The effects of heterogeneity on the retention of radionuclides can then be assessed in the migration analysis for each flow path by applying simulated post-closure flow conditions.

There are a number of potential immobile zones that could be taken into account in the migration analysis. For example, use could be made of the spatial information available on rock types, and especially that related to altered and unaltered rock and the knowledge of the alteration halos in the vicinity of single fractures or deformation zones (see Chapter 4). For any fracture or deformation zone it is possible to divide the rock volume in its vicinity into unaltered and altered zones and fracture filling minerals. Information on the fracture filling minerals is collected during standard core logging and tunnel mapping (although this mapping does not necessarily allow the identification of specific clay minerals that might be present). In contrast, the alteration halo around a fracture is very difficult to map using the naked eye and laboratory tests are needed. C14-PMMA studies of Siitari-Kauppi et al. (2008) and X-ray tomography (Kuva et al. 2009)) clearly show the effect of a single fracture on the porosity and the microstructure of the rock in its vicinity. Porosity investigations will continue, using samples of different fracture types to study the rock adjacent to the fractures and also the characteristics of the fracture fillings. In places, there is a large altered volume of rock surrounding the site scale deformation zones (see Chapter 4), and this information can possibly be used for modelling an immobile zone around a MHZ. The investigation and conceptualisation of the immobile zones that will be assigned to the hydraulic features of the site scale Hydro-DFN model is continuing. The majority of the data will be collected and interpreted as part of the rock characterisation work in the ONKALO access tunnel and in the mapping of drill cores. Table 8-1 summarises the current status of the data evaluation and the plans for future investigations.

The approach taken in the transport modelling is also applicable to the situation where the investigations suggest different retention models for fractures in the different rock domains. For example, the geo-DFN model divides the stochastic background fracturing into two different rock domains: one above structure HZ20 and another below HZ20 (see Section 6.6 for discussion).
Table 8-1. Data to be used in the conceptualisation of the retention models of the hydraulic features. Planned and uncompleted studies are indicated by italics.

<table>
<thead>
<tr>
<th>Immobile zone</th>
<th>Thickness</th>
<th>Porosity</th>
<th>Pore diffusivity</th>
<th>Sorption properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unaltered rock</strong></td>
<td>Unlimited, extent of the connected porosity tested as a part of the in-situ diffusion experiments</td>
<td>C14-PMMA and water gravimetry measurements of the drill core samples</td>
<td>Planned in situ experiments using matrix diffusion tracer test, electrical logging of the formation factor, diffusion of the water vapour when drying the rock surface by nitrogen gas and gas-phase matrix diffusion tracer tests. Comparison with diffusion experiments of the He gas in drill core samples</td>
<td>Batch sorption measurements using drill core samples and major groundwater types</td>
</tr>
<tr>
<td><strong>Altered rock</strong></td>
<td>Thickness estimated from the C14-PMMA measured porosity profiles from the drill core samples, possibly also X-ray tomography</td>
<td>C14-PMMA and water gravimetry measurements of the drill core samples</td>
<td>Based on Archie’s Law He gas measurements using core samples from KR12 interpretation of the He gas measurements on going</td>
<td>Batch sorption measurements using drill core samples and using major groundwater types or Estimated based on the mineralogy, cation-exchange capacity and major groundwater types</td>
</tr>
<tr>
<td><strong>Fracture filling and coating materials</strong></td>
<td>Estimated from drill core samples and ONKALO fracture mapping data. Supported by selected X-ray tomography samples.</td>
<td>C14-PMMA measurements of the drill core samples</td>
<td>Based on Archie’s Law</td>
<td>Batch sorption measurements using drill core samples and using major groundwater types or Estimated based on the mineralogy, cation-exchange capacity and major groundwater types</td>
</tr>
</tbody>
</table>
As an example, concepts are presented for two retention models that have been developed for the water-conducting stochastic background fractures. The two different retention models are for non-filled and filled fractures. Both retention models include immobile zones for unaltered and altered rock. The retention model for filled fractures includes also conceptualisation of the fracture coating and filling materials. In this example the fracture coating and filling materials are separated to different immobile zones (Figure 8-4). However, the final retention model will not be this detailed and the fracture coatings and fillings will be conceptualised as a single immobile zone (cf. also Table 8-1).

The fractures are firstly divided into filled and non-filled fractures (e.g. 77% of the conducting fractures are filled in KR40). Non-filled fractures are simple, joint-type fractures that do not contain fracture fillings and coatings. Filled fractures have more heterogeneous and complex patterns of immobile zones, containing fracture fillings, coatings and altered zones, in addition to the unaltered rock matrix (cf. Figure 8-4).

The quantification of the porosities and thicknesses of the immobile zones is so far based on the C14-PMMA study of the rock matrix properties, using drill core samples from KR38 and KR39 (Siitari-Kauppi et al. 2008). In the future, also x-ray tomography of fractures (Kuva et al. 2009) gives information of mineralogical distribution and small scale structure around different fracture types. Porosity profiles in the rock matrix were measured from the autoradiographs taken from the surfaces of sawn rock samples. Figure 8-1 shows the porosity profile that was measured from the autoradiograph that was taken from KR38 (Sample KR38/5). The profile displays a sharp decrease in the porosity after about 5...20 mm from the fracture wall. Porosity for the first c.a. 10 mm is around 5% as it is only ca. 1% for the rock matrix beyond about 10 mm distance from the fracture wall.

The conceptual model of fractures in Olkiluoto presented here is preliminarily, and is based on small amount of data. In future, it will presumably been improved by new measurements and will also be compared to results of other sites. However, altered halo around fractures is effect of multiphase and usually complicated geological history, and strongly depends on host rock properties and e.g. hydrothermal fluids which were circulating in fracture network.
The same pattern of rock matrix alteration has been applied for both retention models. In addition, the simplified conceptual model of the filled fracture type also encompasses the fracture coatings and fracture fillings. The major fracture-filling minerals (as percentage of fractures containing a filling mineral) in drillholes KR1-40 are clay minerals (49%), Calcite (35%) and Sulphides (31%) (Gehör 2009). Fracture fillings are composed of different combinations of the major filling minerals so that fractures containing only clay minerals are the most common. Other major filling mineral combinations are clay+sulphide, calcite and clay+calcite. Figure 8-2 shows a typical clay filled fracture with a calcite coating that is partly covered by pyrite. Typically, based on the naked-eye estimations in core logging and statistics of fracture data base of KR1-40, the main filling materials, clay and calcite, are about 0.3-0.4 mm thick (Figure 8-3).
Figure 8-2. Typical clay filled fracture with a calcite coating that is partly covered by pyrite (from the core of OL-KR20 in 97.75 m).

Clay thickness

Calcite thickness

Figure 8-3. Distributions of the measured thicknesses of the clay and calcite fracture filling minerals in drillholes KRI-40.

Figure 8-4 shows the conceptual models for the filled and non-filled fractures, as far as they can be quantified based on existing data. The porosities of the filling materials have yet to be systematically measured and they are not included to the conceptual model, although the limited data available indicate that they are greater than 5% (Siitari-Kauppi et al. 2008). Similarly, pore diffusivities have not been measured and they are
not included in the conceptual model in Figure 8-4. However, diffusivities could be estimated based on the porosities and from Archie's Law \( D_e = D_w 0.71 \varepsilon^{0.18} \), where \( D_w \) is molecular diffusivity in free water, \( D_e \) is the effective diffusion coefficient and \( \varepsilon \) the porosity of the immobile zone. In the present example this corresponds to the effective diffusivity in the range of \( 5 \times 10^{-13} \text{ m}^2/\text{s} \) to \( 5 \times 10^{-12} \text{ m}^2/\text{s} \).

The conceptual model of the immobile zone retention properties provides a link to the sorption properties of the radionuclides, as in indicated in Table 8-1. The sorption properties will depend on the radionuclide in question and on the groundwater type and will be reported as part of the safety case data reporting in the Data and Models report. They are evaluated by batch sorption measurements using drill core samples and major groundwater types or estimated based on the mineralogy, cation-exchange capacity and major groundwater types (Table 8-1) and coupled with the immobile layers that are used to construct the conceptual retention models. Estimation of the sorption properties for different immobile zones is supported by presenting the mineralogical composition of the immobile layers as a part of the conceptual retention model (cf. Table 8-1 and Section 4.4.2).

![Figure 8-4. Conceptual model of the immobile zone retention models for the filled and non-filled fractures. Site scale retention models will not separate fracture fillings, but conceptualise them as a single immobile layer.](image)

### 8.2.2 Mobile zones

Flow-related transport properties are simulated by the site scale Olkiluoto Hydro-DFN flow model (Hartley et al 2008). The Hydro-DFN model encompasses the whole of Olkiluoto Island by combining large-scale, hydrogeologically-active zones (HZ) with a
stochastic representation of the less fractured bedrock outside these zones, using a
discrete fracture network concept. The model is parameterised using data from 40 deep
surface KR drillholes, 16 shallow KRB drillholes and 7 PH (Pilot holes) from the
ONKALO tunnel. The fracture data include the geometrical properties of the fractures
and single hole Posiva Flow Log (PFL) measurements. Both hydrogeological zones and
background fractures are assumed to be homogeneous.

Hydraulic tests suggest that the most important hydrogeological zones in the Olkiluoto
site area are HZ19A-C, HZ20A-B and HZ21 and the geological DFN model underlines
the particular importance of HZ20. The Geo-DFN model is divided into two different
fracture domains along the deformation zone that also defines the hydrogeological zone
HZ20. The division of the modelling domain into two different fracture domains is also
used in the Hydro-DFN model. A detailed description of the Hydro-DFN model is given
in Section 6.6 of this report, where the significance attached to HZ20 is discussed.

8.3 Transport Model

Flow and transport simulations have been performed using a detailed scale DFN model
of the repository near field and a site scale DFN model.

The repository near-field model is used to study possible differences in the flow and
transport properties between different Hydro-DFN model variants and for different flow
directions. This model includes only stochastic background fractures. However, analysis
of the role of HZs in the connectivity of the DFN, indicated that the HZ model does not
alter $P_{32, cof}$ in a significant manner (Hartley et al. 2008). Simulations have been repeated
separately for the two deepest depth zones (DZ) that represent possible host rocks for
the repository (see Section 6.6.2 for an explanation of these zones).

The site scale model covers the whole of Olkiluoto Island. It is composed of large,
deterministic hydrogeological zones and the stochastic background fractures, and is
used to assess the transport properties of the release paths from the potential canister
locations.

8.3.1 The repository near-field model

The model domain is a cube with sides of 200 m. Transport simulations have been
repeated for eight different calculations cases: three Case A models applying correlated,
semi-correlated fracture transmissivity-length correlations and a Case B model applying
a semi-correlated fracture transmissivity-length correlation; and in all cases using the
properties of depth zones DZ3 and DZ4. Simulations are calculated only for the FDb
rock domain (see Figure 6.2) that is the dominating fracture domain in the area of the
present-day repository layouts. For the power-law fracture size distribution, small
fractures (with radii down to 0.28 m) have been generated only in the proximity of the
release points. Elsewhere, fractures with radii greater than 2.26 m are generated. The
cases studied are summarised in Table 8-2. See Section 6.6 for a detailed definition of
the Case A and Case B model alternatives.

Pathlines and transport properties are calculated for pressure gradients in the X, Y and Z
directions, using a pressure gradient of 1% in each case. These simulations apply a
simple boundary condition, in order to facilitate the comparison between different
model alternatives and flow directions. The particle pathlines are calculated for 40 realisations of the DFN model.

The particles are released from an array of 100 points in the middle of the model, with the release points being spaced at 5 m intervals. Branching paths are sampled by releasing ten particles at each release point. Particles are released to the connected fractures that are closer than 2.5 m from a particle release point but, if no such connected fracture is found, then no particles are released from that release point (Figure 8-5).

The transport aperture of the fractures is assigned according to the Dershowitz empirical relationship (Hartley et al. 2009): $e_t = 0.46 \sqrt{T}$ where $e_t$ is the transport aperture and $T$ is the fracture transmissivity.

**Table 8-2. Summary of the studied cases.**

<table>
<thead>
<tr>
<th>Model ID</th>
<th>Fracture size distribution model</th>
<th>T model</th>
<th>DZ (masl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-SC-FDb-DZ3</td>
<td>Case A: power-law</td>
<td>SC</td>
<td>DZ3: -150 to -400</td>
</tr>
<tr>
<td>A-SC-FDb-DZ4</td>
<td>Case A: power-law</td>
<td>SC</td>
<td>DZ4: -400 to -1000</td>
</tr>
<tr>
<td>A-C-FDb-DZ3</td>
<td>Case A: power-law</td>
<td>C</td>
<td>DZ3: -150 to -400</td>
</tr>
<tr>
<td>A-C-FDb-DZ4</td>
<td>Case A: power-law</td>
<td>C</td>
<td>DZ4: -400 to -1000</td>
</tr>
<tr>
<td>A-UC-FDb-DZ3</td>
<td>Case A: power-law</td>
<td>UC</td>
<td>DZ3: -150 to -400</td>
</tr>
<tr>
<td>A-UC-FDb-DZ4</td>
<td>Case A: power-law</td>
<td>UC</td>
<td>DZ4: -400 to -1000</td>
</tr>
<tr>
<td>B-SC-FDb-DZ3</td>
<td>Case B: log-normal</td>
<td>SC</td>
<td>DZ3: -150 to -400</td>
</tr>
<tr>
<td>B-SC-FDb-DZ4</td>
<td>Case B: log-normal</td>
<td>SC</td>
<td>DZ4: -400 to -1000</td>
</tr>
</tbody>
</table>
The significant difference in the flowing fracture frequency between depth zones DZ3 (-150 to -400 masl) and DZ4 (below -400 masl) is clearly reflected in the percentage of the deposition hole intersected by a flowing fracture. In the DZ3 about 20% of the simulated deposition holes are intersected by a flowing fracture, whereas fewer than 5% of the simulated deposition holes are intersected by a flowing fracture in the DZ4. Differences in the flowing fracture frequency between different alternative models are small, as can be from the statistics given in Table 8-3.

The retention properties of the alternative models are compared in Figure 8-6, which shows that there are no clear differences between the models. The median values over the different realisations indicate some differences, but the variability between different realisations indicate that in many cases statistically significant results would have required more simulations. The variability between different realisations is large, especially in the case of the deepest depth zone DZ4. The statistics of the minimum and median F (the hydrodynamic control of retention) per realisation are quite similar in the case of DZ4. This follows from the very low number of connected flow paths per realisation in the sparsely fractured DZ4 fracture network. In this respect, the most reliable results are the median F values for depth zone DZ3 that indicates no difference between alternative models.

**Figure 8-5.** Upper left: Model region showing the array of 100 release points in 10 rows. Upper right: Horizontal slice through the model showing the location of the deposition holes. Lower left: Small fractures generated in the vicinity of the release points. Lower right: All fractures generated in the model region.
The outcome of the transport simulations of the background fracturing of depth zones DZ3 and DZ4 has a broader implication concerning uncertainties in the assessment of the retention properties. It may indicate that PFL measurements have a strong correlation with the retention properties, i.e. F along the flow paths. All alternative models are calibrated using the same PFL data and simulations show that they also appear to produce similar retention properties along the flow paths.

**Table 8-3.** Fraction of particles released that are connected to the fracture network in different alternative models.

<table>
<thead>
<tr>
<th>Depth zone</th>
<th>Calculation case</th>
<th>A</th>
<th>A</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture size distr.</td>
<td>Power-law</td>
<td>Power-law</td>
<td>Power-law</td>
<td>Log-normal</td>
<td></td>
</tr>
<tr>
<td>DZ3 -150 ... -400 masl</td>
<td>mean</td>
<td>0.21</td>
<td>0.16</td>
<td>0.22</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>median</td>
<td>0.18</td>
<td>0.17</td>
<td>0.23</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>std</td>
<td>0.16</td>
<td>0.13</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>0.6</td>
<td>0.4</td>
<td>0.68</td>
<td>0.59</td>
</tr>
<tr>
<td>DZ4 -400 ... -10000 masl</td>
<td>mean</td>
<td>0.04</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>median</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>std</td>
<td>0.09</td>
<td>0.08</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>0.42</td>
<td>0.29</td>
<td>0.33</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Figure 8-6. Minimum and median $F$ of the simulated flow paths shown for different alternative DFN models and different flow directions. Notations of the alternative models are: Case A correlated fracture L-T (AC), Case A semi-correlated fracture L-T (AS), Case A uncorrelated L-T (AU) and Case B semi-correlated fracture L-T (BS). Vertical lines show 10% to 90% variability between different realisations. Median $F$ of all realisations is shown by horizontal lines.

8.3.2 The site scale model

The PA transport properties at the site scale have been simulated using a site scale hydro-DFN model and a freshwater flow system. The model has no tunnels or EDZ. By PA transport properties we mean the distributions and moments of the hydrodynamic control of retention ($F [T L^{-1}]$) and the advective travel time along release paths from the potential canister locations. The array of 6816 release points follows the preliminary repository layout (Kirkkomäki 2006). Particles are released only from the release points that have intersecting fractures connected to the flowing fracture network within a radius of 2.5 m from the release point.

The model domain covers the whole of Olkiluoto Island and the discharge areas of the release paths. The transmissivity and geometry of the hydrogeological zones are based on the 2008 hydrostructural model. The boundary conditions applied in the simulations were no-flow on the bottom surface and all vertical sides of the model domain and a specified head on the top boundary that matched the topography. The fractures were generated according to the Case A Hydro-DFN model parameters and used the
calibrated, semi-correlated fracture transmissivity model (cf. Section 6.6). To make the model computationally tractable, the smallest fractures in the large fracture sets were set to a radius of 11.2 m throughout the domain, except around the repository, where smaller fractures were also generated, with a minimum radius of 0.5 m.

In the transport calculations, the transport aperture, \( e_t (L) \) of the fractures was deduced from the cubic law, i.e.:

\[
e_t = 4 e_h = 4 \left( \frac{12 \mu T}{\rho g} \right)^{1/3} \approx 0.04 T^{1/3} \tag{8-1}
\]

where \( e_h [L] \) is the hydraulic aperture and \( T [L^2T^{-1}] \) is the fracture transmissivity. The \( F \) quotient \([TL^{-1}]\) and the advective travel time \( t [T] \) of the fractures were calculated as:

\[
t = \frac{(W e_t L)}{Q} \tag{8-2}
\]

\[
F = \frac{(2 W L)}{Q} \tag{8-3}
\]

where \( W [L] \) is the fracture width, \( L [L] \) is the fracture length and \( Q [L^3T^{-1}] \) is the fracture water flow rate.

Only a few percent of the release points are connected to the flowing fractures, as was the case also in the repository near-field simulations. The exit positions of the flow paths are mainly to the north and to the southwest of the release area. Figure 8-7 shows a plan view of the exit positions for ten realisations. The overall spread in the exit positions is fairly concentrated and governed by the topography and the position of the shoreline. However, large stochastic features seem to play a more important role in determining the exact discharge locations than do the local deterministic zones. However, Figure 8-8 shows the importance of hydrogeological zones HZ21 and HZ099 for the pathway to the north, and although the discharge points do not correspond with the outcrop of HZ21, a large part of the pathway is within HZ21 until a short-cut is found to the top surface of the model through large sub-vertical stochastic fractures.
**Figure 8-7.** Plan view of the exit positions for ten realisations of the model with 350-380 start positions, depending on realisation and ten particles per start position. The exit positions of the ten realisations are shown in different colours. The exit positions in some realisations occur very local.

**Figure 8-8.** The exit positions are mainly to the north and to the southwest of the release area. The participating hydrogeological zones are HZ21 and HZ099.
The statistics of the retention properties are first studied from one realisation. Figure 8-9 shows the histogram of the F quotient for one realisation and Figure 8-10 and Figure 8-11 correlations between flow path F and the initial velocity or initial fracture transmissivity. The spread in retention properties is large, over several orders of magnitude (Figure 8-9). There seems to be a correlation between the total F quotient and the initial water velocity at the start position (Figure 8-10), but a more limited correlation between the total F quotient and the transmissivity values of the initial fracture (Figure 8-11). The flow path of smallest F appears to be group of flow paths with a high initial flow velocity (Figure 8-10).

The four pie charts shown in Figure 8-12 visualise the relative contribution of the hydrogeological zones and the three DFN fracture sets to the total F quotient for different segments of the F quotient distribution. The hydrogeological zones play a minor role, apart from the flow paths of smallest total F quotient. The sub-horizontal (SH) set dominates all parts of the F distribution.

![Figure 8-9](image)

**Figure 8-9.** Histogram of log(F) for a single realisation of the site model with one particle per start position.
Figure 8-10. Scatter plot of total $F$ versus the initial water velocity $v_i$ at the start position for a single realisation of the site model with one particle per start position.

Figure 8-11. Scatter plot of total $F$ versus the initial fracture transmissivity $T_i$ at the start position for a single realisation of the site model with one particle per start position.
Figure 8-12. Four pie charts that show the relative contribution of the hydrogeological zones and the three DFN fracture sets to the total F quotient for four different segments of the F quotient distribution.

Figure 8-13 shows the total F quotient versus the fracture size at the start positions, $r_i$, for a single realisation of the model with ten particles per start position. Low values of the total F quotient can occur, regardless of the size of the initial fracture, presumably because a small fracture can connect directly with a large stochastic fracture or hydrogeological zone. The vertical lines on the right side of this graph correspond to several particles starting in individual large stochastic fractures.
8.4 Interaction with other disciplines

An essential part of the assessment of the retention properties is the DFN flow model, as it has a central role in defining the flow-dependent retention characteristic, the flow paths and the flow rates. The flow paths, which are determined by the flow field, define what immobile zone properties are important for the overall retention. The influence of other disciplines to the transport and retention properties takes place through the DFN flow model.

The DFN flow model is based on the geology, via the geo-DFN model, that provides the basis for the fracture domains in the hydro-DFN model. Potentially water-conducting fractures are also classified, based on the geology. Hydrogeological investigations are used to complete the DFN flow model, by calibrating the connectivity of the network and the hydraulic properties of the fractures.

8.4.1 Uncertainties in migration properties

The geometry of the immobile zones is based on a small number of samples and e.g. determination of different types of fracturing needs more investigations. The bedrock at Olkiluoto, including the fracture properties, has a considerable heterogeneity, which results in uncertainties in the modelled thickness of the altered zones around the fractures. The thicknesses of the fracture infills are rather well known and, for example, different conceptualisations can be developed from the large number of data present. However, data on the retention properties of the fracture filling minerals are still very limited. The subject of the uncertainties associated with the large-scale geological features is presented in Section 4.6.
8.4.2 Uncertainties in flow related properties

The Hydro-DFN model is calibrated in order to reproduce the frequencies of open flowing fractures of the connected fracture network found in the drillholes. Intuitively, the frequency of the flowing fractures is correlated with the distribution of flow between the different flow paths and, in that way, is also correlated with the hydrodynamic control of retention.

The connection between drillhole measurements and the hydrodynamic control of retention can be assessed from simulations of the background fracturing in the repository near field. Alternative models were tested using power-law or log-normal fracture size distributions, different fracture size-transmissivity models and different flow directions. All models were calibrated using the same drillhole and PFL data. The results of the simulations indicate similar F quotient statistics between the different model alternatives, a fact that strengthens the conclusion that uncertainty in the flow-related retention properties is effectively reduced by a proper application of the PFL data.

All DFN models assume that any one fracture has homogeneous properties. The flow rate distribution between different flow paths is determined by the effective transmissivities of the fractures and the use of homogeneous fractures may not have a strong influence on the flow rate distribution between different flow paths. Of greater importance could be that heterogeneity in the fracture planes leads to channelling of the flow. DFN simulations of the flow in the repository near field indicate travel times of years for path length of about 100 m, which means that diffusion in the fracture plane is able to reduce heterogeneities over a few decimetres. The median fracture radius of the background fracturing is about 0.4 m for Case A and about 1.6 m for Case B, which indicates that in-plane heterogeneity of the fractures may not be an issue in the transport simulations.

8.4.3 Implication of uncertainties on predictive modelling

Retention along a flow path is characterised by the retention time, \( t_{ret} \)

\[
t_{ret} \approx \frac{u^2}{\varepsilon^2 R_p D_p} \left( \frac{WL}{Q} \right)^2 \approx \varepsilon K_d \rho D_p \left( \frac{WL}{Q} \right)^2 \text{ if } \varepsilon \ll 1 \text{ and } K_d > 1/\rho
\]  

(8-4)

where \( \varepsilon \) is the immobile porosity, \( R_p \) is the retardation coefficient, \( D_p \) is the pore diffusivity in the immobile pore space, \( K_d \) is the distribution coefficient and WL/Q is the hydrodynamic control of retention. Equation (8-4) indicates that uncertainties in the hydrodynamic control retention have strong influence on the retention, whereas uncertainty in the immobile zone properties results in a much smaller influence on retention.

An efficient way of reducing and estimating uncertainties in the predictive modelling is to focus on the hydrodynamic control of retention. The application of DFN modelling is a major step towards an appropriate description of the flow field, when the transport and retention properties are considered. The resolution of the DFN model can easily be adjusted in order to include smaller fractures where they are needed.
Uncertainty in the flow-related retention properties is approached by applying alternative models. The construction of the DFN model is based on the interpretation of fracture observations in drillholes and aims at developing a connected network of flowing fractures. Alternative models quantify the uncertainties that are associated with the determination of the potentially water-conducting fractures from the fracture database and the parameterisations that influence the connectivity of the fracture network. In the DFN simulations of the repository near field this is realised by Case A and Case B models. Case A applies a power-law size distribution and an upper limit for the intensity of the potentially water-conducting fractures (all open fractures). Case B applies a log-normal size distribution and a lower limit for the intensity of the potentially water-conducting fractures (PFL fractures). Simulation results indicate that the uncertainty associated with the variability between the different realisations is quite large and easily overwhelms the uncertainties between the different model alternatives.
9 PREDICTION OF PROPERTIES IN THE ONKALO AND THE IMPACT OF CONSTRUCTION

9.1 Geological conditions

9.1.1 Introduction

A first set of comparisons of the geological prediction-outcome work for the data from section 0-140 m of the ONKALO tunnel was presented in SR2006 (Andersson et al. 2007), and this Section presents a comparison of geological data from tunnel section 140 to 990 m. Currently, there are a total of 13 A predictions, 7 B predictions without pilot hole data, 7 B predictions with pilot hole data, and 5 outcome reports (Table 9-1). The outcomes and predictions will be documented as separate compilation reports in the near future, focusing on presenting data from each tunnel spiral (that is, 0-1000 m, 1000-2000 m of tunnel length, and so forth). The reader is referred to Andersson et al. (2005) for the nomenclature for the predictions. As the outcomes so far exist only for tunnel section 0-990 m, the section is also the focus of this comparison, excluding the section 0-140 m, which has already been reported in SR2006.

The first part of this Section focuses on a comparison of lithology, ductile deformation, alteration and brittle deformation, whereas the latter Section provides a more detailed account of fracture data evaluation, with additional scanline analyses performed using mapped tunnel data.

Table 9-1. Current status of predictions, outcomes and pilot holes. The focus of this study is highlighted in grey.

<table>
<thead>
<tr>
<th>Tunnel chainage</th>
<th>A Prediction</th>
<th>B Prediction without pilot hole</th>
<th>B prediction with pilot hole</th>
<th>Outcome</th>
<th>Pilot hole ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-140</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>OL-PH1</td>
</tr>
<tr>
<td>135-310</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>ONK-PH2</td>
</tr>
<tr>
<td>310-700</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>ONK-PH3</td>
</tr>
<tr>
<td>700-850</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>ONK-PH4</td>
</tr>
<tr>
<td>840-990</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>990-1190</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>&quot;</td>
<td>ONK-PH5</td>
</tr>
<tr>
<td>1190-1405</td>
<td>0</td>
<td>0</td>
<td>&quot;</td>
<td>&quot;</td>
<td>ONK-PH6</td>
</tr>
<tr>
<td>1405-1560</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>&quot;</td>
<td>ONK-PH7</td>
</tr>
<tr>
<td>1560-1880</td>
<td>0</td>
<td>0</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>1880-1980</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>&quot;</td>
<td>ONK-PH8*</td>
</tr>
<tr>
<td>1980-3100</td>
<td>0</td>
<td>&quot;</td>
<td>0</td>
<td>&quot;</td>
<td>ONK-PH9*</td>
</tr>
<tr>
<td>3100-3200</td>
<td>0</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>3200-3400</td>
<td>0</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
</tr>
</tbody>
</table>

"o" =Documented
"-" =Prediction is not applicable to this tunnel section or outcome is not yet documented
* Under drilling or to be drilled in the near future, corresponding prediction will be finalized after the drilling
9.1.2 Lithology

Predictions and outcome

The outcome and predictions of lithology for tunnel section 140-990\textsuperscript{8} are shown in Figure 9-1 with respect to tunnel length. In the A predictions, the tunnel section from 140-990 m was predicted to consist mainly of diatexitic and veined gneiss, with shorter sections of pegmatitic granite and mica gneiss. Only one prediction B without a pilot hole exists (for tunnel section 840-990 m) and, according to this prediction, this tunnel section consists of veined gneiss, with a pegmatitic granite section occurring at 940-990 m. B predictions with pilot hole data cover about half of the examined tunnel section, however they exclude section 260-700 m, where no pilot holes were drilled. The main rock type in this section is veined gneiss, with shorter sections of pegmatitic granite, diatexitic gneiss and mica gneiss.

\textbf{Figure 9-1.} Predictions and outcome of lithology for chainage 140-990 m of the ONKALO tunnel.

\textsuperscript{8} This refers to the tunnel section from 140 m to 990 m, measured along the length of the tunnel, i.e. what is termed the \textit{chainage}. Such a section of the tunnel could also be referred to as \textit{chainage 140-990 m} or \textit{chainage 140-990}.
Conclusions and suggestions

The predictions of the lithology and the results of the tunnel mapping seem to correspond fairly well, yet a clear discrepancy exists between the resolutions of the data presented in the predictions and in the outcome. The outcome and the A and B without PH data predictions seem to focus on presenting major lithological units or domains, i.e. units with lengths (along the tunnel) of several metres. Prediction B PH, in contrast, provides a very detailed description of the probable conditions in the tunnel, with some lithological units having a length of less than 1 metre (Figure 9-1). This difference in the applied resolution makes reliable comparisons of the predictions, especially the B PHs, and the outcome, very difficult, as it is practically impossible to conclude whether the shorter lithological units, as presented in the predictions, are actually valid.

As an example, in predictions based on pilot hole data, tunnel section 700-840 is predicted to consist of many short pegmatitic granite units, which are not presented in the outcome. Therefore, the question that arises is whether these units actually exist in the tunnel, but were excluded from the outcome due to their small size, i.e. are just thicker sections of leucosome veins, or whether the prediction itself is incorrect?

The resolution applied in the handling of lithological data needs, therefore, to be checked against the requirements of the project and the data presented accordingly. From the perspective of site-scale modelling, the lower resolution and simplification is, of course, preferred, for practical reasons, but for the characterisation of more specific volumes, such as deposition tunnels, a more detailed approach is preferred. Conversely, it can be concluded that the lower resolution predictions, i.e. the A and B without PH data predictions, cannot be employed for very detailed characterisation purposes, but serve the purpose of supplying predictions of the lithology at the site-scale.

B predictions based on pilot hole data are, in contrast, expected to be more suited to the characterisation of more specific volumes of the rock mass. This conclusion is, however, based on the assumption that the pilot hole and tunnel data are directly comparable. Current observations suggest that such a direct comparison may not necessarily be possible, and there needs to be further work carried out, comparing pilot hole data with tunnel data in a more rigorous manner. The current presentation of tunnel data would appear to be an oversimplification in respect to the attainable resolution of the lithology, both from the tunnel mapping and from the pilot holes.

Another issue is whether the current migmatite classification is practical. A major discrepancy seems to exist in the classification of diatexitic and veined migmatitic gneiss types. Long sections of the tunnel, which are classified as veined gneisses, are, however, predicted as being diatexitic gneisses. Experience to date suggests that unambiguous determination of various migmatitic subtypes is quite difficult, not least due to the gradational boundaries between the subtypes. Therefore, the appropriateness of the current migmatite classification system may need to be reconsidered. As the classification originally stemmed from the recognition of migmatite types which could have varying effects on the constructability of the rock, mainly through the existence of weakness planes caused by foliation, it could be worthwhile considering using the foliation classification presented in Milnes et al. (2006) for subdividing the migmatitic gneisses. Additionally, documenting the amount of leucosome and leucosome types in the migmatites could have additional value from the mineralogical and structural perspectives.
9.1.3 Ductile deformation

Predictions and outcome

According to the A predictions, the foliation is expected to dip approximately SE in tunnel section 135-310 m, although no prediction for the angle of dip is given. In tunnel section 310-990 m the dip is expected to be mainly SE, with a shorter section of foliation dipping to the E. The dip is predicted to vary between 20-50° in section 310-700 m, and to be less than 60° in section 700-990 m. The A predictions for the foliation are shown in Table 9-2. According to the outcome, the mean dip of the foliation is approximately SE at an angle in the range of 20° to 70° (Figure 9-2).

Table 9-2. A prediction for the foliation for tunnel section 135-990 m.

<table>
<thead>
<tr>
<th>Chainage</th>
<th>Dip Direction</th>
<th>Dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>135-310</td>
<td>SE</td>
<td>-</td>
</tr>
<tr>
<td>310-420</td>
<td>SSE</td>
<td>20-50°</td>
</tr>
<tr>
<td>420-700</td>
<td>SE to SSE</td>
<td>&quot;Seems to be steeper than 20-50°&quot;</td>
</tr>
<tr>
<td>700-800</td>
<td>SE</td>
<td>&quot;Gentler than approx. 60°&quot;</td>
</tr>
<tr>
<td>800-850</td>
<td>SE or even to E</td>
<td>Gently dipping</td>
</tr>
<tr>
<td>840-990</td>
<td>SE</td>
<td>&quot;Gentler than approx. 60°&quot;</td>
</tr>
</tbody>
</table>

The BPH predictions, together with the outcome for the foliation, are shown in Figure 9-2. The outcome is presented for tunnel sections 0-300 m, 300-600 m and 600-990 m and therefore the foliation data presented in the prediction is clustered into the respective sections in Figure 9-2, excluding section 300-600 m, where there are no pilot hole data. For section 0-300 m, the predicted dip is approximately SE, with the angle of dip varying between 30° to 70°; whereas for section 600-990 m, the dip is E-SE, with the same range of dip angles.
Conclusions and suggestions

As the mean orientation of the foliation is known to be relatively constant at Olkiluoto, it is no surprise that the data in the predictions and outcome agree very well. The small deviations in the data sets may be related to local deformation effects, such as folding. Such effects are difficult to interpret from drillhole data and are probably filtered from the tunnel data, as the foliation measured in the tunnel describes the general or mean orientation of the foliation in a specific tunnel section. The recommendations for the
development of the predictions (and the presentation of the outcome data) are essentially the same as presented in Andersson et al. (2007):

"In order to achieve the maximum amount of information, foliation domains with a certain orientation or type and intensity should be established, both for the predictions and the outcome. In addition, the effect of clustering should be quantified by using, for example, Fisher’s dispersion coefficient (K), which would also give an indication of the uncertainty of the predictions. The level of detail in the predictions need not to be significantly greater than that given in the previous sections, but the most important thing is to give estimates as to whether there are major changes in the direction of foliation and the type and intensity of foliation, as this provides important constraints on the rock mechanical models, the layout adaptation of underground openings and long-term safety (cf. Milnes et al. 2006). Although data from other ductile features, such as fold axes and axial planes, are mainly lacking from the predictions, these data only provide constraints to geological models, and the effect of these on the rock properties and the above-mentioned end users is given in the form of the intensity and type of foliation (e.g. intensely folded rocks with banded foliation are most likely associated with massive rocks or rocks with low-intensity foliation, see Milnes et al. 2006)."

It is recommended that action be taken to develop the processing of the foliation data into domains of specific orientations, type and intensities, as this would yield important information for the end-users of the geological data.

9.1.4 Alteration

Predictions and outcome

In the A prediction, the occurrence of alteration in the first section of the tunnel was given as length intervals of the alteration in nearby drillholes, which of course makes direct comparison with tunnel data difficult. For the tunnel section 310-850 m, pervasive and fracture-controlled kaolinisation was expected, with lesser amounts of sulphidisation and illitisation at chainage 700-850 m. No A prediction for the alteration was given for tunnel section 850-990 m, but according to the B_{without PH data} prediction, pervasive and fracture-controlled kaolinisation, together with pervasive sulphidisation, were to be expected in this tunnel section.

In the B_{PH} prediction, kaolinite and illite were expected as fracture fillings, similarly to sulphidisation in the tunnel section covered by pilot hole PH2. Yet, all predictions were given as a function of pilot hole length and no predictions of alteration were given for tunnel sections outside the pilot hole data. Nevertheless, a fractured and strongly-weathered section was predicted for section 251-530 m. No B_{PH} prediction for the alteration was provided for tunnel section 700-840 m. Tunnel section 840-990 m was predicted to contain fracture-controlled, and only in places, pervasive kaolinisation, as well as pervasive sulphidisation. Illite was predicted to be met only sporadically in this tunnel section.

According to the tunnel mapping, the first 700 m of the tunnel is affected by pervasive kaolinisation, which is greatest at the locations of the high-grade ductile deformation zones. Chloritisation of micas is also common in the first 700 m of the tunnel. In chainage 700-990 m, kaolinisation is weak and mostly fracture-controlled, whereas the
amount of sulphidisation has increased. The distribution of various fracture minerals is shown in Figure 9-3 – calcite, kaolinite and pyrite are the dominant fracture minerals in most of the chainages. The amount of kaolinite in the fractures decreases towards the end of the first 700 m of the tunnel and the amount of pyrite increases. Clay occurs more frequently in the first half of this section, but is also found at the intersections of the deformation zones towards the end of the tunnel section. Illite is mostly found in chainage 200-300 m (the northernmost parts of this section of the ONKALO).

![Figure 9-3](image)

**Figure 9-3.** The fracture filling data for different sections in respect to the alteration minerals occurring in fractures, in ONKALO chainage 0-990 m. Calcite (CC), illite (IL), kaolinite (KA), pyrite (SK) and unidentified clay minerals (SV).

**Conclusions and suggestions**

As already noted in the comparison of alteration data from tunnel section 0-140 m (Andersson et al. 2007), the predictions and the outcome seem to correspond well at the scales considered. The conclusions regarding the development of the predictions are therefore the same as those presented in Andersson et al. (2007):

“In general, it can be noted that the level of detail in the predictions and outcome is quite low and, as a consequence, the comparison can only be of a qualitative nature. In order to increase the likelihood of a more quantitative comparison, the level of detail needs to be increased for both the outcome and the predictions, possibly to include more detailed analysis on the possible correlation between fracturing and alteration; for example, do certain fracture orientations/types correspond to certain type of alteration. Similarly, the possibility that alteration is related to observed or predicted deformation zones needs further investigation.”
The importance of assessing whether there are specific structural controls on the occurrence of alteration (i.e., certain types of fractures, high-grade zones, lithology or fault zones) is emphasized, as this would improve the predictive capability of the models. In addition, it is suggested that more detailed comparisons of pilot hole and tunnel data should be conducted, in order to assess the resolution that is both attainable and practical from the existing data sets. In the current predictions and outcomes the resolution of the data is quite low.

9.1.5 Brittle deformation – zone intersections

Tunnelchainage 135-310 m - predictions and outcome

Both the A and B predictions for tunnelchainage 135-310 m predict the occurrence of deformation zone intersections. The A prediction, based on bedrock model 2003/1 of Vaittinen et al. (2003) and supplemented by all available new data collected after finishing this model (i.e., investigation trench and borehole data, and geophysical data), gave three possible zone intersections (Table 9-3). The B prediction, which was based on the A prediction, but supplemented by investigation data obtained from pilot hole ONK-PH2, also predicted three intersections. No deformation zone intersections were, however, identified in chainage 135-240 m during the tunnel mapping, contrary to both the A and B predictions (Table 9-3).

Table 9-3. Predicted and observed deformation zones for tunnel chainage 135-310 m.

<table>
<thead>
<tr>
<th>Prediction type</th>
<th>Location in the tunnel (m)</th>
<th>Character</th>
<th>Dip/dip direction</th>
<th>Class</th>
<th>Location in the tunnel (m)</th>
<th>Dip/dip direction</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>170-180</td>
<td>possible fracture zone</td>
<td>subhoriz.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>228-230</td>
<td>hydraulic structure</td>
<td>subhoriz.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>260 -&gt;</td>
<td>weathered/fractured zone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>251.20-ca. 350</td>
<td>weathered/crushed zone</td>
<td>67.4/143.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>253.09-256.90</td>
<td>strongly weathered, altered and fractured section</td>
<td></td>
<td></td>
<td>ONK-HGI-24000-28230</td>
<td>240-282.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ONK-BFI-24250-28700</td>
<td>242.50-287</td>
<td>17/009</td>
</tr>
<tr>
<td>B</td>
<td>286.50-293.70</td>
<td>strongly weathered section</td>
<td>42/134</td>
<td></td>
<td>ONK-BFI-29200-29500</td>
<td>292-295</td>
<td>42/273</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ONK-BFI-30950-31100</td>
<td>309.50-311</td>
<td>36/153</td>
</tr>
</tbody>
</table>

Three of the four intersections mapped from the tunnel walls can, more or less, be correlated with two of the deformation zone intersections suggested by the B prediction: the weathered, altered and fractured section predicted at 253.09-256.90 m is "enclosed" within the high-grade deformation zone intersection observed at 240.00-282.30 m and the brittle fault intersection at 242.50-287.00 m; and the predicted strongly-weathered section at 286.50-293.70 m roughly coincides with the intersection observed at 292-295 m. The predicted dip of the latter intersection (42°) is identical to that observed, but the dip direction differs noticeably (134° and 273°, respectively). The deformation zone intersection observed at 309.50-311.00 m was not predicted.

Tunnelchainage 310-700 m - predictions and outcome

For tunnel section 310-700 m, only an A prediction was made, again being based on the bedrock model 2003/1 of Vaittinen et al. (2003) and supplemented by all available new data.
The prediction suggested that nine deformation zones might intersect the tunnel within chainage 310-700 m; and directional information was provided for three of them (Table 9-4). During the mapping of the tunnel, nine deformation zone intersections were also identified. Comparing the predicted intersections with those mapped from the tunnel, a good correlation in locations can be found: only one of the mapped intersections, at chainage 324.40-328.00 m, cannot be correlated with any predicted zone and only two predicted zones, at chainages 512.00-513.30 and 640-700 m, lack their "real-life" counterparts (Table 9-4). The predicted fractured section at 512-521 m is represented by two narrow brittle fault intersections (516.10-517.20 and 521.50-523.00 m) in the outcome, whereas the rest are correlated one-to-one.

Table 9-4. Predicted and observed deformation zones for tunnel chainage 310-700 m.

<table>
<thead>
<tr>
<th>Prediction type</th>
<th>Location in the tunnel (m)</th>
<th>Character</th>
<th>Dip/dip direction</th>
<th>Class</th>
<th>Intersection ID</th>
<th>Location in the tunnel (m)</th>
<th>Dip/dip direction</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>395-415</td>
<td>fractured zone</td>
<td></td>
<td></td>
<td>ONK-BFI-32440-32800</td>
<td>324.40-328</td>
<td>50/158</td>
<td>RiIV</td>
</tr>
<tr>
<td>A</td>
<td>401.70-412</td>
<td>strongly weathered section</td>
<td>42/134</td>
<td></td>
<td>ONK-BFI-39400-40700</td>
<td>394.407</td>
<td>50/138</td>
<td>RiIV</td>
</tr>
<tr>
<td>A</td>
<td>438.40-464.80</td>
<td>major fractured zone</td>
<td>67.4/143.5</td>
<td></td>
<td>ONK-HGI-44970-45330</td>
<td>449.70-453.30</td>
<td>56/158</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>478-500</td>
<td>strongly fractured section</td>
<td></td>
<td></td>
<td>ONK-BFI-48830-48900</td>
<td>488.30-489</td>
<td>25/317</td>
<td>RiIII</td>
</tr>
<tr>
<td>A</td>
<td>512-513.30</td>
<td>strongly fractured section</td>
<td></td>
<td></td>
<td>ONK-BFI-51610-51720</td>
<td>516.10-517.20</td>
<td>79/233</td>
<td>RiIV</td>
</tr>
<tr>
<td>A</td>
<td>556-585</td>
<td>fractured section</td>
<td></td>
<td></td>
<td>ONK-HGI-56530-56670</td>
<td>565.30-566.70</td>
<td>50/130</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>610</td>
<td>potential deformation zone</td>
<td></td>
<td></td>
<td>ONK-BFI-61650-61730</td>
<td>616.50-617.30</td>
<td>39/131</td>
<td>RiIV</td>
</tr>
<tr>
<td>A</td>
<td>640-700</td>
<td>possible fractured section</td>
<td>NW-SE, N-S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The orientation of the major fractured zone predicted for chainage 438.40-464.80 m correlates well with that of the high-grade intersection observed at 449.70-453.30 m (orientations of about 67°/144° and 56°/158°, respectively), even if the nature of the intersection does not (i.e. brittle as compared with ductile). The orientation of the strongly-weathered section at 401.70-412.00 m was also predicted (42°/134°), but it differs clearly from that of its observed counterpart, the brittle fault intersection at 410.00-419.95 m (85°/065°). Another ductile deformation intersection is observed at 565.30-566.70 m, which correlates with the fractured section predicted for 556.00-585.00 m.

Tunnel chainage 700-840 m - predictions and outcome

Both A and B predictions were made for tunnel chainage 700-840 m. The A prediction was based on the bedrock model 2003/1 of Vaittinen et al. (2003) supplemented by all available new data; the B prediction, made use of data from pilot hole ONK-PH3 and a tentative geological model of the ONKALO area (later published as Paulamäki et al. 2006).

The A prediction suggested two possible deformation zone intersections, at 720-730 m and 750-773 m (Table 9-5). The former can be roughly correlated with the only observed zone intersection at 713.10-718.05 m, even though the predicted and observed orientations disagree by about 90° (Table 9-5).
Table 9-5. Predicted and observed deformation zones for tunnel chainage 700-840 m.

<table>
<thead>
<tr>
<th>Prediction type</th>
<th>Location in the tunnel (m)</th>
<th>Character</th>
<th>Dip/dip direction</th>
<th>Class</th>
<th>Intersection ID</th>
<th>Location in the tunnel (m)</th>
<th>Dip/dip direction</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>716.30-718.80</td>
<td>fractured zone</td>
<td></td>
<td>RiIII-RiIV</td>
<td>ONK-BFI-71310-71805</td>
<td>713.10-718.05</td>
<td>68/041</td>
<td>RiIII-RiIV</td>
</tr>
<tr>
<td>A</td>
<td>720-730</td>
<td>potential deformation zone</td>
<td>NW-SE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>814.91-815.84</td>
<td>fractured zone</td>
<td>RiII</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>816.96-817.26</td>
<td>fractured zone</td>
<td>RiII</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The B prediction gave locations and classes of three possible deformation zones (Table 9-5). The location of the deformation zone suggested at 720-730 m in the A prediction is adjusted to 716.30-718.80 m, and the character of the intersection is predicted as a RiIII-RiIV fractured zone. This correlates well with the observed RiII-RiIV brittle fault zone at 713.10-718.05 m. The two RiII fractured zones predicted toward the end of the tunnel section have no match in the outcome.

Tunnel chainage 840-990 m - predictions and outcome

Both A and B predictions for tunnel chainage 840-990 m predicted the occurrence of deformation zone intersections; the B with PH data prediction also exists for this chainage, but did not suggest such an occurrence. The A prediction was based on the bedrock model 2003/1 of Vaittinen et al. (2003), whereas the B prediction utilised the site-scale geological model of Paulamäki et al. (2006).

No deformation zone intersections were suggested by the 2003/1 bedrock model, but the existence of a local hydraulic feature at 950-960 m was suggested in the A prediction, based on borehole data. The location of this suggested feature roughly matches that of two intersections reported in the outcome, a brittle fault zone and a high-grade ductile intersection, both at 931.90-963.00 m (Table 9-6).

Table 9-6. Predicted and observed deformation zones for tunnel chainage 840-990 m.

<table>
<thead>
<tr>
<th>Prediction type</th>
<th>Location in the tunnel (m)</th>
<th>Character</th>
<th>Dip/dip direction</th>
<th>Class</th>
<th>Intersection ID</th>
<th>Location in the tunnel (m)</th>
<th>Dip/dip direction</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>950-960</td>
<td>local hydraulic feature</td>
<td></td>
<td></td>
<td>ONK-BFI-90020-90640</td>
<td>900.20-906.40</td>
<td>56/090</td>
<td>RiIV</td>
</tr>
<tr>
<td>B</td>
<td>958-964</td>
<td>deformation zone OL-BFZ051</td>
<td></td>
<td></td>
<td>ONK-HGI-93190-96300</td>
<td>931.90-963</td>
<td>45/006</td>
<td>RIV</td>
</tr>
<tr>
<td>B</td>
<td>969.70-974.80</td>
<td>deformation zone OL-BFZ018</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The site-scale geological model, the B prediction, implied the presence of two deformation zones close to the end of the studied tunnel section, at 958-964 m and 959.70-974.80 m. The former can be roughly correlated with the local hydraulic feature of the A prediction and the two above-mentioned intersections in the outcome. The third observed intersection, a brittle fault zone at 900.20-906.40 m (Table 9-6), has no correlation with the predictions.
Conclusions and suggestions

A total of eight predictions were made for chainage 135-990 m and the seven that predicted the locations of deformation zone intersections are listed in Table 9-7. The following comments and suggestions can be made from reviewing the predictions, and comparing the information provided in them with the mapping data from the ONKALO tunnel:

1) The naming of the predictions does not follow current practice and is somewhat misleading. The three A predictions for tunnel section 135-840 m (Table 9-7) were based on the bedrock model 2003/1 of Vaittinen et al. (2003) and on additional geological and geophysical data, and should, therefore, be called B predictions, according to current definitions. Similarly, the two B predictions for the same tunnel interval should be referred to as $B_{PH}$ (B with PH data) predictions, as pilot hole data were used. The A prediction for tunnel section 840-990 m is based solely on the bedrock model, so the name is appropriate; the B prediction for the same tunnel section is also made purely on the basis of a model (the site-scale geological model of Paulamäki et al. 2006), and should, perhaps, also be also termed an A prediction. For clarity, future predictions should be named following the definitions for the various types of predictions (A, B, $B_{PH}$), as defined in Andersson et al. (2005).

Table 9-7. Predictions, predicted and observed deformation zone intersections, and the success rate of predictions for chainage 135-990 m.

<table>
<thead>
<tr>
<th>Chainage (m)</th>
<th>Prediction type</th>
<th>Intersections</th>
<th>Successful</th>
<th>Intersections</th>
<th>Successful</th>
<th>Intersections</th>
<th>Successful</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>prediction</td>
<td>predictions</td>
<td>predicted</td>
<td>predictions</td>
<td>(%)</td>
<td>predicted</td>
</tr>
<tr>
<td>135-310</td>
<td>&quot;A&quot;</td>
<td>3</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>&quot;B&quot;</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>66.7</td>
<td>75</td>
</tr>
<tr>
<td>310-700</td>
<td>&quot;A&quot;</td>
<td>9</td>
<td>9</td>
<td>7</td>
<td>8</td>
<td>77.8</td>
<td>88.9</td>
</tr>
<tr>
<td>700-840</td>
<td>&quot;A&quot;</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>&quot;B&quot;</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>33.3</td>
<td>100</td>
</tr>
<tr>
<td>840-990</td>
<td>A</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>100.0</td>
<td>66.7</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>50.0</td>
<td>66.7</td>
</tr>
</tbody>
</table>

2) Only four predictions (the two A predictions covering the tunnel chainage 135-700 m and the two B predictions for 700-990 m) present the information on possible deformation zone intersections using a clear, tabular format, which is easy to access; for the remainder, only text and various figures are provided. In the future, a table summarising the information on deformation zone intersections should be included in the predictions, to make the data easier and faster to find, and the prediction itself more unambiguous. The table should provide at least the location (tunnel chainage) and character (a short description) of each predicted zone and, if possible, their orientation (trend or dip/dip direction) and class (for example, RiIII) should also be included.

3) For the tunnel section 135-990 m, a total of 23 intersections were predicted, 13 of these (57%) can be correlated with intersections observed during tunnel mapping. These 13 successful predictions cover 14 of the 17 observed deformation zone intersections (82%). There is, however, considerable variation in the success rate of the predictions.
between the different tunnel sections and prediction types, although no clear pattern is evident (Table 9-7). In tunnel section 135-310 m, none of the zones suggested by the A prediction match the outcome, whereas two out of three zones (66.7%) in the B prediction can be correlated with the observed zone intersections, and include all but one of them (75%). The A prediction made for tunnel chainage 310-700 m is much more successful: seven out of the nine predicted zones (77.8%) match the outcome and successfully predict eight of the nine observed intersections (88.9%). The A and B predictions both succeed in predicting the only deformation zone intersection mapped from tunnel section 700-840 m, but give one and two intersections, respectively, with no match to the outcome. In tunnel section 840-990 m, two out of the three observed intersections (66.7%) are predicted successfully by both predictions, but one deformation zone suggested by the B prediction (based on the site-scale geological model) is not seen in the outcome. It would seem that predictions utilizing additional geological, geophysical and pilot hole data are, in general, slightly more successful in predicting the location of deformation zone intersections than the predictions based solely on existing models. There are, however, only two true A predictions made for the studied tunnel segment (see comment 1 above), so more data - more predictions, outcomes and their comparisons - are required to see if any systematic variation emerges in the success rates between the different types of predictions. It should be noted, however, that all the predictions seem to give a reasonable idea of the general frequency of deformation zones within each tunnel section, as the number of zone intersections in each prediction is similar to their number in the outcome.

4) The current models mainly describe site-scale, major structures, whereas more local, smaller-scale features are mapped from the tunnel. This difference in resolution explains some of the discrepancies between the predicted and observed deformation zone intersections. For example, the A and B predictions for tunnel section 135-310 m suggest the presence of at least a 100 m wide deformation zone from chainage 250 m onwards. In the tunnel, deformation zones are often observed as areas of more intense fracturing or ductile deformation, which can be recognised and mapped at a scale of metres to some tens of metres. Thus, within the chainage of the predicted aforementioned broad deformation zone, at least five different deformation zone intersections of variable orientation are observed, which makes comparison and correlation impossible. It is, therefore, suggested that more local features should be incorporated into the modelling, so that in the future more accurate, tunnel-scale predictions could be produced. This will be particularly relevant as the main research/repository level is reached. Also, as stated in the prediction/outcome comparison for tunnel chainage 0-135 m (Andersson et al. 2007): "Geophysical anomalies thought too weak to be included in the prediction as possible zone intersections could be presented as a separate table, with possible explanations given in the outcome. This would increase the sensitivity of the predictions constructed in the later phases”.

5) The current practice of comparing predicted features with the outcome, only after the mapping is completed, makes it difficult to try to assess if alternative explanations for the predicted features could be found; even if they cannot be correlated with mapped deformation zone intersections. The correlation process would be improved, if predictions preceding the systematic and zone intersection mapping phases of the tunnel could be made use of. Thus, the locations of predicted intersections could be studied by paying attention to the possible explanations for the modelled features, and possible "unpredicted" deformation zones could also be specifically noted.
6) The predicted deformation zone intersections are correlated with the observed ones on the basis of location (tunnel chainage). Even when correlation between the predicted and the observed zones is good, slight discrepancies do occur. When zones are predicted on the basis of surface geophysical data, these differences are, at least partly, caused by issues related to resolution. In relation to predictions based on pilot hole data, the explanation given in the prediction/outcome comparison for tunnel chainage 0-135 m (Andersson et al., 2007) still applies: "The slight deviations in the predicted locations may be a result of the methods used to collect the data - the locations of the predicted intersections are … determined by their occurrence in the pilot holes, whereas the observed intervals are measured from the midpoint of the tunnel, one metre above the tunnel floor, and this is likely not the location of the actual pilot hole". The suggested procedures are also still valid: "Therefore, the location of the defined intersection interval, e.g. one metre above the tunnel floor, should be stated in the prediction. Similarly, any uncertainty in the predicted location of a deformation zone (for example, location ± x metres) should be stated, in order to increase confidence in the prediction".

7) Orientations were not given for all predicted deformation zone intersections, and directional information exists only for four predicted intersections successfully correlated with observed features (Table 9-3 to Table 9-5). As only one of these predicted orientations is a rather close match to that observed in the tunnel (a major fractured zone/high-grade zone intersection in Table 9-4, with predicted and observed orientations of 67°/143° and 56°/158°, respectively), it seems that orientations are difficult to predict with any level of accuracy. This is partly explained by natural variations in the orientation of fault surfaces; other possible reasons for this discrepancy need further consideration.

8) Class was predicted only for the three intersections given in the B prediction for tunnel section 700-840 m (Table 9-5), and only one of the intersections could be correlated with an observed deformation zone. For that intersection, the correlation was good (predicted RiIII-RiIV, observed RiII-RiIV).

9.1.6 Brittle deformation – fractures

In the study of Tuominen et al. (2006), a discrepancy was observed between the fracture data from pilot hole OL-PH1 with the fractures mapped on the walls of the tunnel, although the underlying reasons for this were not assessed. As a consequence, the discrepancy is further analysed in this section by comparing fracture data from pilot holes ONK-PH2, ONK-PH3 and ONK-PH4 (see Figure 9-4 and Figure 9-5) with the fracture data from the corresponding sections of the tunnel, i.e. focusing on the assessment of the B predictions. In addition, a preliminary assessment of the underlying reasons for the discrepancy is also provided.

Data and methods

The data set used was composed of the fracture data from pilot holes ONK-PH2 (Öhberg et al. 2005), ONK-PH3 (Öhberg et al. 2006b) and ONK-PH4 (Öhberg et al. 2006a) (see Figure 9-4 and Figure 9-5), and the fracture data from the corresponding sections of the tunnel. As the fracture data from the ONKALO tunnel consists of 3D traces of the mapped fractures and the corresponding fracture attributes, a direct comparison of the data was not possible. Therefore, for the calculation of \( P_{10} \) (fractures/metre) values from the ONKALO fracture data, “pseudo pilot holes” (PPH)
were projected on to the digitised 3D fracture trace map, on the right wall of the tunnel (Figure 9-6) and the corresponding $P_{10}$ values were calculated from the intersections of the PPHs and the fracture traces.

Figure 9-4. Locations of pilot holes ONK-PH2, ONK-PH3 and ONK-PH4 in the ONKALO. Top view.

9 It is emphasised that the selection of the "right wall of the tunnel" has no specific implications and is just a matter of choice for the present study.
Figure 9-5. Locations of pilot holes ONK-PH2, ONK-PH3 and ONK-PH4 in the ONKALO. View to the north.

Figure 9-6. Example of fracture data from the tunnel wall. Pilot hole ONK-PH2 and traces of fractures mapped from the ONKALO wall. The Z-axis is scaled 5 times with respect to the X- and Y-axes.
The pilot hole (PH) projections were treated as virtual pseudo pilot holes (PPH) on the tunnel wall and were logged through and all intersecting fracture traces were identified. Fracture numbers were picked up from Surpac Vision string files, where fractures are digitised and connected to all corresponding fracture attribute data. In the tunnel mapping data, a set of similar fracture types is often digitised into the database as one fracture, yet the real number of fractures and the space between them are mentioned in the list of fracture attributes. Based on this information, a fracture trace which actually consists of a fracture cluster, was counted as multiple fractures in the PPH line. If this kind of trace were intersected twice with a PPH, the total number of fractures was divided and spread in two sets.

Thus, the result was a fracture list from the PPHs, which could be directly compared with the actual pilot hole fracture data, although fracture attributes of the PHs and PPHs were not entirely coherent. The information common to both of hole types was depth, dip, azimuth, filling minerals and thickness, and the $J_r$ and $J_a$ values of fractures. Fracture frequencies were counted for 10 m hole sections.

**Fracture frequency**

Fracture frequencies are considerably lower in the PPHs than in the PHs - the $P_{10}$ values in PPHs are over 50% lower than the corresponding values in PHs (Table 9-8). Calculated fracture frequencies are plotted in Figure 9-7 - Figure 9-9. Some similar trends can be observed, but PPH data are scaled down in comparison with the PH data and the $P_{10}$ value is almost always higher in the PH data.

<table>
<thead>
<tr>
<th></th>
<th>PH LENGTH</th>
<th>PH FRAC NUMBER</th>
<th>PH $P_{10}$</th>
<th>PPH LENGTH</th>
<th>PPH FRAC NUMBER</th>
<th>PPH $P_{10}$</th>
<th>DIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>92.31</td>
<td>254</td>
<td>2.75</td>
<td>92.31</td>
<td>87</td>
<td>0.94</td>
<td>-65.7%</td>
</tr>
<tr>
<td>3</td>
<td>144.91</td>
<td>185</td>
<td>1.28</td>
<td>144.91</td>
<td>87</td>
<td>0.60</td>
<td>-53.0%</td>
</tr>
<tr>
<td>4</td>
<td>96.01</td>
<td>329</td>
<td>3.43</td>
<td>96.01</td>
<td>147</td>
<td>1.53</td>
<td>-55.3%</td>
</tr>
</tbody>
</table>
**Figure 9-7.** Fracture frequency in the pilot hole and pseudo pilot hole 2.

**Figure 9-8.** Fracture frequency in the pilot hole and pseudo pilot hole 3.
Figure 9-9. Fracture frequency in the pilot hole and pseudo pilot hole 4.

Orientation

Fracture orientation observations are shown in Figure 9-10 to Figure 9-15. Fracture poles are drawn as squares, which are colour-coded by the length intervals of the pilot holes to visualise spatial changes. The diagrams are contoured using Fisher concentrations (Figure 9-16) and weighted using the Terzaghi correction, with a bias angle of 15°.

In the case of ONK-PH2 and PPH2, the orientation of the fracturing appears to differ considerably (Figure 9-10 and Figure 9-11). The strong maximum of fractures parallel to the general foliation trend (dipping to the SE) can be seen in PH2 data, but not in PPH2. In PPH3, and evidence of PH3’s sub-horizontal E-dipping maximum can be found. Also, a weak indication of PH3’s SW-dipping fracture cluster can be seen in the last intervals of PPH3 (Figure 9-12 and Figure 9-13). The best congruence can be observed in the PH4 and PPH4 data (Figure 9-14 and Figure 9-9), where the main cluster in both fracture data is SE-dipping with additional sub-horizontal fracturing. Also, the vertical, N-S trending fractures display significant clusters. The maximum of the vertical ESE-WNW-trending fractures is weak in PPH4, but can still be seen. In general, no systematic spatial changes in fracture orientations are observed in either the PPH or PH data. ONKALO tunnel wall data used in PPH measurements contains several sets of fractures in the same orientation. These sets are naturally calculated in contouring but can be confusing in diagram when only one point is plotted.
Figure 9-10. Fracture orientations in ONK-PH2. Equal area, lower hemisphere projection.

Figure 9-11. Fracture orientations in ONK-PPH2. Equal area, lower hemisphere projection.
Figure 9-12. Fracture orientations in ONK-PH3. Equal area, lower hemisphere projection.

Figure 9-13. Fracture orientations in ONK-PPH3. Equal area, lower hemisphere projection.
Figure 9-14. Fracture orientations in ONK-PH4. Equal area, lower hemisphere projection.

Figure 9-15. Fracture orientations in ONK-PPH4. Equal area, lower hemisphere projection.
Fisher concentrations % of total per 1 % area

<table>
<thead>
<tr>
<th>PH2,PH3,PH4</th>
<th>PPH2</th>
<th>PPH3,PPH4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1</td>
<td>0 - 2</td>
<td>0 - 2.5</td>
</tr>
<tr>
<td>1 - 2</td>
<td>2 - 4</td>
<td>2.5 - 5</td>
</tr>
<tr>
<td>2 - 3</td>
<td>4 - 6</td>
<td>5 - 7.5</td>
</tr>
<tr>
<td>3 - 4</td>
<td>6 - 8</td>
<td>7.5 - 10</td>
</tr>
<tr>
<td>4 - 5</td>
<td>8 - 10</td>
<td>10 - 12.5</td>
</tr>
<tr>
<td>5 - 6</td>
<td>10 - 12</td>
<td>12.5 - 15</td>
</tr>
<tr>
<td>6 - 7</td>
<td>12 - 14</td>
<td>15 - 17.5</td>
</tr>
<tr>
<td>7 - 8</td>
<td>14 - 16</td>
<td>17.5 - 20</td>
</tr>
<tr>
<td>8 - 9</td>
<td>16 - 18</td>
<td>20 - 22.5</td>
</tr>
<tr>
<td>9 - 10</td>
<td>18 - 20</td>
<td>22.5 - 25</td>
</tr>
</tbody>
</table>

**Figure 9-16.** Fisher contouring legend for stereo plots in Figure 9-10 to Figure 9-15.

**Fracture fillings**

The mineralogy of the fracture infills was compared, using information from the total counts of single mineral fillings and from mineral-filling combinations. Up to 13 fracture filling minerals have been detected from tunnel wall fractures intersected by PPHs and from pilot hole fractures. The percentages of fractures with specific filling minerals are plotted as histograms in Figure 9-17. A common trend is seen in the PH and PPH data, but chlorite- and biotite-bearing fractures are only abundant in the PH data. The PH data also show considerably larger percentages of kaolinite and calcite, whereas in the PPH data pyrite and clay are more common.

The six most common fracture filling mineral combinations from both data sets are plotted in Figure 9-18. Three of these combinations are found in both data sets: kaolinite, calcite+pyrite and pyrite. The most common combinations cover a higher portion of all fractures in PHs, because the PH data seem to have fewer combinations. The PPH data suggest a greater number of multi-mineral fillings, such as calcite+chlorite+ kaolinite+pyrite and biotite+kaolinite+pyrite.

Filling thicknesses are distributed quite consistently between the holes (see Figure 9-19 - Figure 9-21). The only anomalous feature is a high percentage of 0.5-1.0 mm thick fillings in PH4 and PPH 4. The thicknesses seem to be, or are estimated to be, lower in the PH data. A large number of fractures with thicknesses less than 0.5 mm are present in every case. Thickness intervals greater than 0.5 mm are almost always more common in the PPH data.
Figure 9-17. Percentages of fractures with certain fracture filling mineral in PHs and PPHs.
Figure 9-18. Percentages of most common filling mineral combinations in PPH and PH data. CC=calcite, KA=kaolinite, KL=chlorite, SK=pyrite, BT=biotite, SV=clay.

Figure 9-19. Approximate fracture filling thickness (mm) in PH2 and PPH2 data.
Figure 9-20. Approximate fracture filling thickness (mm) in PH3 and PPH3 data.

Figure 9-21. Approximate fracture filling thickness (mm) in PH4 and PPH4 data.
**J_r and J_a parameters**

In the Q classification system J_r values describe the roughness of fracture surfaces and J_a values their alteration. Low J_r values describe fractures with low friction, i.e. slickensides and smooth fractures, and high values, correspondingly, fractures with higher friction (rough, discontinuous fracture surfaces); low J_a values denote fractures with no or only slight alteration and high values thick, clay-bearing fractures. In this study, J_r and J_a values were correlated hole by hole. The J_r value distributions of the holes are shown in Figure 9-22 to Figure 9-24. Similar general trends can be seen in every J_r distribution, but the number of J_r values of 1.5 and 2.0 are more common in ONK-PH2 than in other pilot holes. One prominent feature is the small number of J_r 2.0 values in ONK-PPH3 and ONK-PH4. The most marked difference between the PHs and PPHs is in the J_r 3.0 values, which are very high in the PHs, and clearly lower in the PPHs. Also, the smallest J_r values (1-2) seem to be in general more common in the PPHs than in the PHs.

The distributions of J_a values are well-correlated in PH and PPH 3 and 4 (Figure 9-26 and Figure 9-27) but in PPH2 the percentage of J_a value 2 is notably lower and the percentage of values 3 and 4 markedly higher compared with PH2 (Figure 9-25).

![Figure 9-22. J_r number distributions in ONK-PH2 and ONK-PPH2.](image-url)
**Figure 9-23.** $J_r$ number distributions in ONK-PH3 and ONK-PPH3.

**Figure 9-24.** $J_r$ number distributions in ONK-PH4 and ONK-PPH4.
Figure 9-25. $J_a$ number distributions in ONK-PH2 and ONK-PPH2.

Figure 9-26. $J_a$ number distributions in ONK-PH3 and ONK-PPH3.
Figure 9-27. $J_a$ number distributions in ONK-PH4 and ONK-PPH4.

Conclusions and suggestions

Two types of incoherence can be found in the pilot hole and mapped tunnel fracture data: (1) practical differences, such as the different methods used for mapping fracture attributes from the core and the tunnel wall, which depend on the way in which the mapping is carried out, the different mapping scales and sometimes even on variations in the opinions of geologists; and (2) unavoidable differences, such as the large number of single mineral fillings seen in pilot hole data and biases in orientation distributions, which depend on the geometry of the features being mapped.

The total number of fractures is clearly higher in the pilot hole data compared with the tunnel data. The main reasons for this are evidently the totally different mapping conditions in the tunnel and in the drill core laboratory and the bias in fracture size cut-off, caused by the sizes of the respective sampling volumes. The systematic tunnel mapping must often be carried out within a constrained period and, despite the lighting system, the tunnel is still moist, partly in shadow and in places dirty, whereas the mapping conditions in the drill core laboratory are obviously much better.

The significant absence of fractures parallel to the foliation in the tunnel data can be explained by the characteristics of the excavated tunnel wall. The migmatites at Olkiluoto are usually pervasively foliated and the rock typically cleaves along the mica-rich layers. These kinds of cleaved surfaces can be very common, but tend not to be noticed as fractures in the tunnel wall, or at least mapped as fractures, as they remain closed under the stress conditions (although some of these cleaved planes are indeed fractures *sensu stricto*). In contrast, in the drill core these features will tend to open up,
due to the effects of stress relief, and are more easily mapped as true fractures. This effect effectively biases the frequencies of fractures controlled by the foliation.

The small number of fracture poles in the PPHs lower hemisphere figures is visually confusing, but can sometime be partly explained by clustering of a set of similar fractures into a single fracture during the mapping. Therefore, some of the poles presented in the stereograms denote several fractures, which of course affects the contouring.

The high clay mineral content in tunnel data may be due to the mainly dark and moist conditions of the tunnel. Fillings, which can be specified more accurately to be, for example, kaolinite and illite in a drill core, may be defined simply as clay in the tunnel wall. In addition, larger surface areas of fractures can be seen in the tunnel, and, as a consequence, several different fracture fillings may be found, in contrast to the small fracture surfaces seen in drill cores.

The high frequency of $J_r$ numbers 1.5 and 3 is understandable, because the majority of fractures are rough and planar (1.5) or rough and undulating (3). The large percentage of $J_r$ values of 3 in the pilot hole data is probably a consequence of the mapping scale, as most of fractures show some (small-scale) undulation at the scale of a drill core and can, therefore, be classed as undulating. In contrast, on the tunnel wall, fracture profiles will often be visible over large length scales, and may then be classed as planar, regardless of any centimetre-scale undulation that might be present.

The best agreement regarding $J_a$ numbers is shown by PH4 and PPH4. The relative absence of small numbers in the PPH data can be explained by the difficulty in detecting fractures with small $J_a$ on the tunnel walls. Fractures with higher $J_a$ values are usually associated with more visible surfaces and are thus easier to observe.

The relatively good congruence of $J_r$ and $J_a$ values between the PH and PPH data may indicate that the classification method is appropriate.

Several difficulties can exist in trying to compare the fracture data from pilot holes with data from the tunnel walls. Firstly, the existing data sets need time-consuming manual modifications in order to be in comparable forms. Secondly, significant discrepancies in the data sets can become evident only after the comparison has been performed, and, therefore, more intensive comparisons and data processing of the fracture data need to be carried out. In the future, an automatic method needs to be produced for producing organized fracture data sets and for calculating fracture frequencies, etc. for "pseudo pilot holes". Also, fracture data acquisition methods need to be calibrated continuously to detect any discrepancies.

### 9.1.7 General conclusions and suggestions

#### Lithology

A and B predictions, without the use of pilot hole data, are appropriate for evaluating site-scale lithological properties of the bedrock, but the scale of these predictions is not adequate for predicting small-scale phenomena in the tunnel. Predictions based on pilot hole data are, in contrast, more suited for predicting more detailed conditions. Before acting on this conclusion, however, the pilot hole data needs to be compared more
rigorously with the tunnel data, as the current presentation of the tunnel data seems to be an oversimplification with respect to the resolution that is possible to attain, both from the tunnel and from pilot holes.

The current classification of migmatites may need to be reconsidered, to ensure that it is appropriate and practical with respect to the project, as there seem to be major problems in identifying the various migmatite types with a high level of confidence. As the classification originally stemmed from the need to recognise migmatite types that could have varying effects on the constructability of the rock, mainly through the existence of weakness planes caused by foliation, it could be worthwhile to consider using the foliation classification presented in Milnes et al. (2006) for the subdivision of the migmatitic gneisses. Additionally, documenting the amount of leucosome and leucosome types in the migmatites could have an additional value both from a mineralogical and a structural perspective.

**Ductile deformation**

The conclusions regarding the development of the predictions (and the presentation of outcome data) are essentially the same as those presented in Andersson et al. (2007). It is recommended that actions are taken to develop the processing of foliation data into domains of specific orientations, types and intensities, as this would yield important information for the end-users of the geological data. The most appropriate scale, or scales, for this processing should be dictated by the needs of the end-users and, therefore, the development of a programme for processing foliation data should be performed in an integrated manner with other disciplines.

**Alteration**

Predictions seem to correspond well with the outcome at the scales considered. It is, however, suggested that the pilot hole and tunnel data should be compared in a more detailed manner, as this would provide more constraints on the practical and attainable resolution of the alteration data. The current level of detail in the predictions and the outcomes is quite low and is probably insufficient for the characterisation of deposition tunnels and disposal holes.

It is also suggested that further investigations should take place on the possible structural controls which might affect the occurrence and extent of alteration. At the site scale, it is known for example that the illitisation is closely associated spatially with site-scale fault zones; however, there may be further constraints when the situation is analysed at a more detailed scale, which could be revealed by investigating both the tunnel and pilot hole data in more detail. The possible relationship of certain types and orientations of fractures with the associated alteration should also be further investigated.

**Brittle deformation – zone intersections**

Based on the comparison, it can be seen that all the predictions seem to give a reasonable idea of the general frequency of deformation zones within each predicted tunnel section, as the number of zone intersections in each prediction is similar to their number in the outcome. In addition, it seems that predictions that make use of additional geological, geophysical and pilot hole data are, in general, slightly more successful in predicting the location of deformation zone intersections than the predictions based
solely on existing models. Nevertheless, more detailed analyses are still required to see if any systematic variation emerges in the success rates between the different types of predictions.

The current models mainly describe site-scale, major structures, whereas more local, smaller-scale features are mapped from the tunnel. This difference in resolution explains some of the discrepancies between the predicted and the observed deformation zone intersections. It is, therefore, suggested that more local features should be incorporated into the modelling, so that more accurate, tunnel-scale predictions could be produced in the future. This would probably require the development of tunnel-scale models, which would be constructed in parallel with site-scale models. Local-scale models, which would mainly incorporate pilot hole data, are likely to be especially relevant, as the main research/repository level is reached and the first panels and deposition tunnels are characterised.

The statement given in the prediction/outcome comparison for tunnel chainage 0-135 m in Andersson et al. (2007) is still valid: "Geophysical anomalies thought too weak to be included into the prediction as possible zone intersections could be presented as a separate table, with possible explanations given in the outcome. This would increase the sensitivity of the predictions constructed in the later phases". The assessment of a prediction’s success could also be partly carried out at the mapping phase, and the locations of predicted intersections could be studied in detail, especially in cases where predicted features did not correlate with mapped deformation zone intersections.

**Brittle deformation - fractures**

Major differences exist between the fracture data obtained from the pilot holes and that obtained from the tunnel, with the difference being most pronounced in fracture frequency data – the frequencies in the tunnel data being more than 50% lower than that from the pilot holes. There may be several reasons for these results, but, in general, two levels of incoherence can be found in the pilot hole and mapped tunnel fracture data: (1) fracture attributes may be mapped differently in the core and on the tunnel walls, which will depend on the conditions under which the mapping is carried out, the different mapping scales and sometimes even the different opinions of the geologists; and (2) unavoidable differences, such as the large number of single mineral fillings in pilot hole data and the biases in orientation distributions, which will depend on the geometry of the mapped features and the biases caused by the different sizes of the sampling volumes.

There can be several difficulties in trying to compare fracture data from pilot holes and from the tunnel walls. Firstly, the existing data sets need time-consuming manual modifications in order to be in a comparable form. Secondly, significant discrepancies in the data sets can be found when the comparison is carried out. Therefore, more intensive comparisons and data processing should be carried out with the fracture data and, in the future, an automatic method needs to be produced for producing organized fracture data sets and calculating fracture frequencies, etc. for "pseudo pilot holes". Also methods of fracture data acquisition need to be calibrated continuously to detect any discrepancies.
9.2 Rock mechanics

9.2.1 Introduction

Much of the information concerning the rock properties is generated by the Geology personnel and the prediction-outcome aspects have been described in Section 9.1. The direct rock mechanics prediction-outcome studies have been mostly orientated towards calibrating the predictions of rock spalling and in developing a better understanding of the stress-strength conditions.

9.2.2 Rock mechanics P-O work

The rock mechanics prediction-outcome work has concentrated on predictions of rock spalling in the ONKALO and on comparisons with the observations. The predictions involve a knowledge of the rock stress and the rock strength and will vary according to the orientation of the ONKALO tunnel sections and their depth.

Figure 9-28 illustrates the spalling prediction and observed rock falls for the ONKALO ramp at depths from 195 to 296 m (chainage 2080–3135 m). The spalling potential was based on the stress orientation (NW-SE) that was assumed at the time that the prediction was made, on the maximum tangential stress criterion and on the use of the spalling strength as a proportion of the unconfined compressive strength; for the spalling potential estimate here 0.57 UCS strength was used (Hakala et al. 2008). The ONKALO tunnel was divided to 17 sections, based on its profile and orientation and depth location. Within each stress region, the stress has a triangular shaped probability distribution, where the maximum and minimum values are as for the generic assessments. The maximum and minimum concentrated stresses for each tunnel section were calculated using Examine3D a three dimensional boundary element code.

At these depths, the spalling predictions suggest that there is a 1% and 10% probability of spalling in the regions highlighted by different colours, noting that this leg of the ONKALO ramp is mostly orientated NW-SE, i.e. sub-perpendicular to the assumed direction of the maximum in situ horizontal stress. The percentage probability of failure incorporates both the probability of failure itself, plus the amount of spalling that will be experienced in a particular location. The prediction for the next tunnel loop under construction (chainages 3117-4340 m), assuming an east-west in situ stress orientation, is presented in Figure 9-30 - the east-west stress orientation reflecting the current understanding of the in situ stress (see Section 5.2.1).
Figure 9-28. Predicted locations where the highest probability of spalling occurs (1% and 10%) in the ONKALO ramp (third loop) are highlighted by different colours and observed rock falls marked as stars.
Figure 9-29. Spalling prediction for the fourth ONKALO tunnel loop with east-west situ stress orientation.

Stars in Figure 9-28 indicate the observed rock damage – which accords quite well with the prediction, because almost all of the damage is in the NE-SW trending tunnel sections or in a region where the stress has been concentrated by adjacent excavation.

By continuing such prediction-outcome studies, it will be possible to calibrate the analysis prediction methodology more fully, although a statistical approach will have to be retained because of the inherent variability of the host rock.

Additionally, work has been undertaken concerning the displacement responses (convergence measurements) at the -180 m level, due to the excavation of the personnel shaft (Figure 9-32 and Figure 9-34), and the drillhole data (Pilot holes) versus tunnel data (Figure 9-36…Figure 9-43).

As shown in Figure 9-32, the magnitude of the measured maximum displacement (about 1.1 mm) was in the predicted range (Figure 9-3). Convergence measurement results at that depth level, however, indicated a different stress orientation (~N-S) from that predicted (E-W). This result was later supported by the strain measurement campaign at the same location.
As seen in Figure 9-36...Figure 9-43 the GSI value (the rock quality) could be sometimes hard to estimate from the drillhole data, which can be easily understandable due to the heterogeneity of the rock mass, even at small scales, as has already been emphasized in Chapter 5. There are systematic differences (Figure 9-35) or very limited correlations (Figure 9-36). Drillhole data also indicate more variation for the GSI values (Figure 9-34 and Figure 9-38). The heterogeneity and different mapping window may explain the differences, but this difference needs to be investigated further. Also, it needs to be remembered, as discussed in Chapter 5, that the accuracy of the drillhole estimate can be considered to be ± one Q' class (see also Figure 9-39).

![Figure 9-30](image)

**Figure 9-30.** Predicted displacement contours and vectors around the Ø4.5 m shaft and the location of first five extensometer anchors points. Maximum predicted displacement was 1.1 ± 46% mm. Assumed major stress orientation was E-W.
Figure 9-31. Measured displacements around the Ø4.5 m shaft. Maximum measured displacements were 1.1 mm and the direction is close to N-S, i.e. indicating the major stress component to be N-S rather than E-W.

Figure 9-32. GSI values estimated from pilot hole PH1 vs. GSI values obtained from the mapping of the ONKALO tunnel. A reasonable match is found between the drillhole and tunnel data. Coloured areas (left) indicate the intersections of the fracture zone.
Figure 9-33. GSI values estimated from pilot hole PH2 vs. GSI values obtained from the mapping of the ONKALO tunnel. A reasonably good match is found between the drillhole and tunnel data.

Figure 9-34. GSI values estimated from pilot hole PH3 vs. GSI values obtained from the mapping of the ONKALO tunnel. No clear correlation is found in this case. Coloured areas (left) indicate the intersections of the fracture zone.
**Figure 9-35.** GSI values estimated from pilot hole PH4 vs. GSI values obtained from the mapping of the ONKALO tunnel. The drillhole data indicate a better GSI value. Coloured areas (left) indicate the intersections of the fracture zone.

**Figure 9-36.** GSI values estimated from pilot hole PH5 vs. GSI values obtained from mapping of the ONKALO tunnel. No very clear correlation is found in this case. Coloured areas (left) indicate the intersections of the fracture zone.
Figure 9-37. GSI values estimated from pilot hole PH6 vs. GSI values obtained from mapping of the ONKALO tunnel. More scatter is found in the drillhole data.

Figure 9-38. GSI values estimated from pilot hole PH7 vs. GSI values obtained from mapping of the ONKALO tunnel. Good correlation is found.
Figure 9-39. Difference in GSI value; GSI Tunnel – GSI PH.

In Figure 9-39, the y-axis is the absolute value of the difference in the GSI values, as measured in the tunnel and in the pilot holes at the corresponding chainages. The data curve in Figure 9-39 is similar to a cumulative distribution curve, except that the sample number is here on the x-axis: for example, 50% of the samples account for all the GSI differences for 7 GSI units or less, which is equivalent to approximately one Q’ class.

9.2.3 Conclusions

As is illustrated in Figure 9-28 to Figure 9-43, the prediction-outcome exercises are most useful in calibrating the utility and accuracy of both the estimation of rock properties and the output from numerical analyses using the rock property data. It is intended that these exercises should continue as the ONKALO descends – so that it can be demonstrated that the rock mechanics information and analytical methodology are supported by a well-founded basis of rock mechanics conditions at Olkiluoto.

9.3 Hydrogeological impacts

The open tunnels and shafts of the ONKALO, and the subsequent repository, are likely to create a hydraulic disturbance to the site's groundwater system for hundreds of years (e.g. inflow of groundwater into the open tunnels and drawdown of the groundwater table, intrusion of surface water containing oxygen and carbon dioxide deep into the bedrock, and upconing of deep saline groundwater). The objective of this work was to assess the potential hydrogeological disturbance of the excavation of the ONKALO and the accuracy of the previous predictions (Andersson et al. 2007), and also to provide new predictions for the inflow, the evolution of the groundwater levels and the hydraulic heads at the monitoring points during the whole period of construction. In
addition, the evolution of the salinity distribution (in particular, the possible upconing of deep saline groundwater) in the vicinity of the tunnels was considered.

Due to the computational expense, the phenomena referred to above were analyzed separately using somewhat different modelling approaches and assumptions. The evolution of the groundwater levels and hydraulic heads were simulated by employing the free-surface approach, in which only the saturated zone is included in the modelled volume, and the evolving water table constitutes a free surface. The salinity was neglected in these simulations. The evolution of the salinity distribution was simulated by employing a coupled (flow and salt transport) and transient model and by ignoring the possible displacement of the water table.

The modelling was based on the current 2008 flow model, which has been calibrated against the undisturbed baseline observations (responses from the pumping tests performed in 1992-2004, pressure and salinity in deep drillholes). The simulations were carried out with a finite element program package FEFTRA, which has been developed at VTT for groundwater flow modelling (Löfman et al. 2007). A summary of the study is provided below. The details (the approach, the assumptions, the input data, the calibration, the results and the sensitivity analysis) will be presented in the background report on the modelling (Löfman et al. 2009).

### 9.3.1 Modelling the ONKALO tunnels

The modelling was based on the ONKALO layout of March 2008 (Figure 9-40). All the tunnels were modelled explicitly, according to the layout and taking into account the progress of the excavations, using a stepwise excavation schedule. The annual or bi-annual averages of the actual excavation rates over the period 2004-2007 were applied for the excavation of the ONKALO. The latest bi-annual rate was applied after 2007.

The conceptual geometry of the 3-D tunnel system was simplified to a wireframe model, in which each tunnel segment was represented by a line located in the centre of the actual segment, i.e. no physical extension (such as would be defined by a radius) was considered. Each line (tunnel) segment was modelled as a set of nodes of the finite element mesh by using an appropriate (internal) boundary condition for each node, i.e. the hydraulic sink boundary condition was used for the open tunnels.
Figure 9-40. The ONKALO layout of March 2008. The nearest tetrahedral finite elements adjacent to the ONKALO are presented on the top. Due to the grouting and/or the positive skin, the hydraulic conductivity of the elements, which represent the sparsely fractured rock, was decreased to obtain an acceptable agreement between the observed and calculated inflows. On the bottom the nearest drillholes to the ONKALO and the selected drillhole sections of KR25 and KR37, in which the hydraulic heads and/or TDS concentration in Figure 9-43, Figure 9-44 and Figure 9-49 are presented.
9.3.2 Calibration

Grouting, which is being applied during the excavation and operational phases of the ONKALO and the repository, in order to limit the inflows, reduces the conductivity of the hydrogeological zones (HZ) and the sparsely fractured rock (SFR) in the vicinity of the tunnels. The grouting has been applied to limit the inflows from the HZs and, at shallow depths, also to limit inflow from the SFR. At greater depths, grouting of the SFR has proved to be unnecessary, because of the general decrease in permeability of the SFR with depth and because the permeability of the rock tends to decrease transverse to the tunnels, due to mechanical coupling, leading to a decrease in fracture apertures (referred to as positive skin).

The site-scale flow model is a simplified, larger-scale description of the bedrock. In the flow model the hydraulic characteristics of the SFR are modelled using the equivalent porous medium (EPM) approach, in which the fractured system is treated as a single continuum with the effective hydraulic conductivity. The effective conductivity is based on the measured, small-scale values, which were averaged to obtain the representation of the similar overall behaviour of the fracture network on a larger length scale (the site scale). Whereas the effective conductivity is valid in characterising the overall groundwater flow conditions in the bedrock, locally (e.g. near the ONKALO) its validity may be more restricting. This is manifested by an excessive calculated inflow, when the conductivity of the SFR below a depth of 50 m remains the same as the surrounding bedrock in the well-characterised area. Thus, in order to compensate for an excessive effective conductivity around the ONKALO, and to obtain a match between the calculated and observed inflow, the conductivity needs to be decreased. The decrease is based on the positive skin, because the effect of very few transmissive fractures deeper in the bedrock has already been considered implicitly in defining the effective conductivity.

In the modelling the effects of grouting and positive skin were taken into account by adjusting the hydraulic conductivity of the SFR and the transmissivity of the intersecting HZs around the tunnels. The effect of grouting was implemented by decreasing the transmissivity of the triangular finite elements (representing the HZs) adjacent to the tunnels and the hydraulic conductivity of the tetrahedral finite elements (representing the SFR) adjacent to the tunnels (Figure 9-40). The average length of the sides of the grouted tetrahedra and triangular elements was about 4 m, which means that the grouting and the positive skin in the model extended to somewhat greater distances from the tunnel walls than is actually the case.

The values for the conductivity and transmissivity in the vicinity of the tunnel were acquired by calibrating the calculated inflow against the observed total inflow into the tunnel (Vaittinen et al. 2008b). As a result of the calibration, the transmissivity of the HZs at the intersection of the tunnels (Table 9-9) and the hydraulic conductivity of the SFR at all depths around the tunnels (Table 9-10) were decreased, in order to obtain an acceptable agreement between the observed and calculated inflows. The grouting efficiency at the intersections of the tunnels and HZs was selected, so that the total inflow from the HZs remains about 3-5 L/min, corresponding to the observations (so far the proportion of the inflow from the HZs has been minimal compared with that of the SFR). The effect of the grouting efficiency and the positive skin on the hydraulic conductivity of the SFR around the tunnel was determined on the basis of the inflows observed up to the end of 2007 (the data freeze date) and to a depth of -250 m. For the SFR around the part of the tunnel that it to be excavated after the data freeze, to a depth of -540 m, similar values to those found at -250 m depth were assumed.
Table 9-9. The transmissivity \( [m^2/s] \) of the hydrogeological zones (HZ) in the vicinity of the ONKALO and elsewhere. The transmissivity near the ONKALO was decreased to obtain the acceptable agreement between the observed and calculated inflows. In SR2006 (Andersson et al. 2007) the grouting efficiency in the HZs was adjusted to \( 1.0 \times 10^{-8} \) m/s.

<table>
<thead>
<tr>
<th></th>
<th>Base value</th>
<th>ONKALO</th>
<th>Basis of the adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>HZ19A</td>
<td>2.6 \times 10^{-5}</td>
<td>5.0 \times 10^{-9}</td>
<td>Grouting</td>
</tr>
<tr>
<td>HZ19B</td>
<td>3.2 \times 10^{-7}</td>
<td>5.0 \times 10^{-9}</td>
<td>Grouting</td>
</tr>
<tr>
<td>HZ19C</td>
<td>6.3 \times 10^{-5}</td>
<td>5.0 \times 10^{-9}</td>
<td>Grouting</td>
</tr>
<tr>
<td>HZ20A</td>
<td>1.5 \times 10^{-5}</td>
<td>5.0 \times 10^{-9}</td>
<td>Grouting</td>
</tr>
<tr>
<td>HZ20B</td>
<td>9.0 \times 10^{-6}</td>
<td>5.0 \times 10^{-9}</td>
<td>Grouting</td>
</tr>
</tbody>
</table>

Table 9-10. The hydraulic conductivity \([m/s]\) of the sparsely fractured rock (SFR) in the well-characterised area (the rock volume where the drillhole investigations have been focused, WCA) and in the vicinity of the ONKALO. The conductivity near the ONKALO (Figure 9-40) was decreased to obtain the agreement between the observed and calculated inflows. In SR2006 (Andersson et al. 2007) the conductivity was adjusted to \( 5.0 \times 10^{-9} \) m/s in the upper 50 m layer only, due to the lack of observations.

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>WCA</th>
<th>ONKALO</th>
<th>Basis of the adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td>1.0 \times 10^{-7} - 3.2 \times 10^{-8}</td>
<td>2.0 \times 10^{-9}</td>
<td>Grouting</td>
</tr>
<tr>
<td>50-100</td>
<td>3.2 \times 10^{-8} - 5.0 \times 10^{-9}</td>
<td>5.0 \times 10^{-10}</td>
<td>Positive skin</td>
</tr>
<tr>
<td>100-200</td>
<td>5.0 \times 10^{-9} - 1.3 \times 10^{-10}</td>
<td>5.0 \times 10^{-11}</td>
<td>Positive skin</td>
</tr>
<tr>
<td>200-400</td>
<td>1.3 \times 10^{-10}</td>
<td>5.0 \times 10^{-11}</td>
<td>Positive skin</td>
</tr>
<tr>
<td>400-540</td>
<td>3.0 \times 10^{-11}</td>
<td>3.0 \times 10^{-11}</td>
<td>No adjustment</td>
</tr>
</tbody>
</table>

*) The logarithm decreases linearly at a depth interval.

In the free surface approach used for simulating the evolution of the groundwater levels and hydraulic heads, there is one additional parameter (infiltration), which affects the transient behaviour of the system. The infiltration was determined by calibrating it against the observed groundwater level, which by the end of 2007 had varied by only a small amount. Using the current flow model, the average infiltration rate of 2.0% (of the annual precipitation of 550 mm) resulted in a groundwater level which differed least from the undisturbed long-term mean.
9.3.3 Results

The simulations were carried out from the start of the ONKALO excavations (September 2004) up to the (assumed) start of the excavation of the repository facilities in 2015, and show that the open tunnels draw groundwater from all directions in the bedrock. Following the advance of the excavations, the flow directions start to change in the vicinity of the tunnels, first in the sparsely fractured rock (SFR) and then in the hydrogeological zones (HZ), after their direct (HZ19 and HZ20) or indirect (HZ004, HZ21 and HZ099) connections to the open tunnels. The grouting and the positive skin do not completely isolate the tunnels from the surrounding bedrock, but substantially reduce the hydraulic disturbance. The flow pattern remains essentially similar, but the magnitude of the groundwater flow is much lower than when no control of the groundwater inflow is assumed.

Inflow

The results of the monitoring programme since SR2006 (Andersson et al. 2007) show that the 2006 flow model clearly overestimated the hydraulic impact of the ONKALO (Figure 9-41). The calculated total inflow was too high, because of overestimating the volume of water derived from the SFR. In 2006 the calibration of the grouting efficiency was based on four measurements that had been made at tunnel chainage 580 m and two measurements at chainage 990 m, which gave average inflows of 10 and 17 L/min, respectively. The consequence of this calibration against the average values at these two observation points, resulted in the HZs intersecting the tunnels being grouted so as to have a transmissivity of $1.0 \times 10^{-8} \text{ m}^2/\text{s}$. In addition, the hydraulic conductivity of the SFR was not allowed to exceed $5.0 \times 10^{-9} \text{ m/s}$. Thus, due to the lack of inflow data, the conductivity around the tunnels was adjusted only for the uppermost 50 m, whereas the properties of the SFR around the tunnels at greater depths remained unchanged, with the resulting overestimation of inflows.
Figure 9.41. The calculated total inflow of groundwater into the ONKALO tunnels (the access tunnel, three shafts, the main and the lower characterization level). The acronyms HZ and SFR stand for the total inflow coming from the hydrogeological zones and the sparsely fractured rock between the zones, respectively. Dashed lines denote the times when the access tunnel pierces the HZs. The circles represent the observations at the certain points of chainage, measured at several different times up to the end of 2007 (Vaittinen et al. 2008), and are related only to the chainage axis of the figures, not the time axis.

Significantly more information on the inflows (about 150 observations) was available for this modelling update (Vaittinen et al. 2008b). Ignoring the high leakage from the grouting and pilot holes at a chainage of approximately 1400 m, the total inflow had been stabilized to about 20 L/min by the end of 2007 (the data freeze). After calibrating the hydraulic properties around the tunnels, the current flow model was able to capture the observations very well. The calculated inflow increases with time, following the advance of the excavations. A notable increase occurs after the access tunnel and the shafts intersect the HZ20 system in 2008 and at the beginning of 2010, respectively. Finally, after the whole tunnel system has been excavated, the total inflow is predicted to be 35 L/min, of which 77% is derived from the SFR and 23% from the HZs. This is in accordance with reality, as most of observed water flow into the ONKALO takes place along single fractures within the SFR. The calculated inflow from the SFR, however, is evenly distributed along the tunnels, because the single fractures have not...
been considered explicitly in the flow model, but have instead been included implicitly in determining the effective hydraulic conductivity. In 2006 the calculated total inflow was 66 L/min.

The grouting and the positive skin do not completely isolate the tunnels from the geological environment, with the result that the calculated inflow was sensitive to the hydraulic conductivity of the surrounding SFR. The use of the alternative hydraulic conductivity ($K_1$, see Table 6.2), which was from a depth of 200 m, at a greater depth than the one selected as the base case value ($K_2$), increased the inflow deeper in the bedrock, resulting in about 40% higher total inflow (50 L/min).

Groundwater level

The groundwater level in shallow holes varied by only a little during 2007 (Vaittinen et al. 2008b) and the possible impact of the ONKALO on the water table has, so far, been minimal. The differences found between the reference holes (representing the natural fluctuation of the groundwater level) and other holes are so small, that it is not possible to determine if they are due to the ONKALO or to the effects of other construction activity. However, according to the preliminary analysis, the tunnel may have caused some minor (0.1-0.2 m) long-term changes in the groundwater level in the Liiklansuo area (to the south of the ONKALO) and near the surface intersection of HZ19A at drillhole KR12. The flow model 2006, however, predicted a steady depression of the groundwater table, and as a chainage of 3000 m is reached by the end of year 2008, the water table is slightly below sea level in one shallow observation point. Once again, the excessive assumed inflow is the primary reason for the discrepancies between the observations and the calculations. Assuming values for the infiltration and the flow porosity which are too low, which then affect the transient behaviour of the water table, may be an additional reason for the differences (the predicted evolution of the water table is sensitive to the selection of the infiltration parameters).

Because the groundwater level has varied only a little and the impact of the ONKALO has, so far, been minimal, the infiltration in the free surface model was determined, so that the calculated water table would be as close as possible to the undisturbed long-term mean by the end of 2007. The acceptable water table was obtained with an average infiltration rate of 2% (of the annual precipitation of 550 mm). The current model predicts that the water level will decrease by a few metres, and only in the vicinity of the ONKALO, by 2012 (Figure 9-42). The highest drawdown occurs near the surface intersections of HZ19A and HZ19C, which are connected directly to the ONKALO access tunnel.

The calculated groundwater level depends on, and is sensitive to, the infiltration, the flow porosity, the transmissivity of the HZs extending to the surface and the hydraulic conductivity of the uppermost layer of the SFR. The interplay between the infiltration and the flow porosity is responsible for the transient behaviour of the water table.
Figure 9.2. The calculated evolution of the groundwater table in the vicinity of the ONKALO. The lowest point is about 4.4 m above sea level in the vicinity of the shafts at 2012. The observed drawdown of the water table has been minimal so far.
Figure 9-43. The calculated (with the previous 2006 flow model and the current 2008 flow model) and the observed hydraulic heads in selected packed-off sections of drillhole KR25. See Figure 9-40 for the location of the sections. The times, at which the tunnels pierce the HZs passing through the drillhole sections or the rock near the sections, are denoted by dashed lines.
Figure 9-44. The calculated (with the previous 2006 flow model and the current 2008 flow model) and the observed hydraulic heads in selected packed-off sections of drillhole KR37. See Figure 9-40 for the location of the sections. The times, at which the tunnels pierce the HZs passing through the drillhole sections or the rock near the sections, are denoted by the dashed lines.
Hydraulic heads in the deep drillholes

The assessment of the hydraulic heads is performed along the deep packed-off drillholes, from which the most representative and comprehensive time series of data have been obtained (Vaittinen et al. 2008b). The changes in head observed in these drillholes (KR1, KR9, KR12, KR23, KR25 and KR37) can also most probably be attributed to the excavation of the ONKALO. The highest long-term drawdowns have been detected in KR23 and KR25, whereas in KR37 high drawdowns had already been observed at the beginning of the monitoring in Autumn 2007. All the three drillholes are located close to the tunnels and the correlation between the inflow and drawdown is evident in the observations. The main source of this disturbance is due to the inflow to the tunnel, and the 2006 flow model thus also overestimates the impact of the ONKALO on the hydraulic heads in the shallow observation holes and along the deep packed-off drillholes. Discrepancies between the calculated and observed heads of up to several metres were detected for some drillholes (Figure 9-43 and Figure 9-44).

A good match between the calculated and observed hydraulic heads was obtained using the current flow model. The calculated heads in all sections of KR23 and KR25 (Figure 9-43) decrease slowly, whereas the observed values have stabilized or have started to recover, the difference is, however, only minimal. The evolution of the head field follows the advance of the excavations, in particular when the access tunnel intersects the HZs. The small decrease can be observed in the shallowest sections (L7 and L8) of KR25 after the tunnel intersects HZ19, whereas a larger drop occurs in the section L3 after the tunnel and three shafts have intersected HZ20A, which passes through L3. The model predicts the head in KR25 to be at its lowest at about -3 m, after all the tunnels and shafts have intersected the HZ20 system in 2010. The model was also able to capture relatively well the high drawdowns (~25 m) observed in KR37 at the beginning of the monitoring period (Figure 9-44). The HZ19 system passes through the sections L2-L4, which is clearly reflected in the head field. The lowest section L1 is not intersected by the HZs, but is located very close to the access tunnel and all the three shafts, resulting in a high drawdown (~35 m) during 2007-2008, after the access tunnel has passed L1 and all the shafts have been excavated to a depth 290 m.

The transient behaviour of the calculated heads was sensitive to the assumed flow porosity and also, but to a lesser extent, to the infiltration. Because the evolution of the head field follows the advance of the excavations, the applied average excavation rate also affects the results.

Groundwater salinity

The assessment of the TDS concentration was based on the monitoring data from the ONKALO and the deep drillholes up to the end of 2007 (Pitkänen et al. 2008; Figure 9-45), which consisted of 121 deep groundwater samples collected from about 20 different open or multi-packered drillholes. The ONKALO data consisted of 24 samples from three groundwater stations (ONK-PVA1−PVA3) and 27 samples from 19 leaking fractures (ONK-RV1−RV19). Most of the monitored groundwater samples have been measured from single fractures, which are interpreted as being part of the SFR.

In general, the drillhole samples are very similar to the baseline data. Most of the monitoring samples taken from the deep drillholes near the ONKALO represent intersections of HZ20A. Unfortunately, the TDS values from HZ20A were of little value for the current work, because they have been affected by the presence of open...
drillholes, which have not been included in the flow model. The observations are also composed in the main of single samples scattered throughout the bedrock, i.e. most of the samples have been measured in different sections of different drillholes at different times. Thus, no time series of observations showing the potential effect of the excavations is available and the length of the monitoring period has also been too short to obtain a proper time series. A small number of changes have, however, been observed, but they result more likely from the presence of open drillholes rather than from the ONKALO.

Figure 9-45. The monitoring TDS data from the ONKALO and the deep drillholes (KR1-37, a depth of 0-600 m) since the excavation of the ONKALO started (September 2004) until the end of 2007 (Pitkänen et al. 2008). The ONKALO data were measured at three groundwater stations (ONK-PVA1–PVA3) and 19 leaking fractures (ONK-RV1–RV19). The drillhole data markers in the figure are located in the centre of the packed-off sections, the vertical lines denoting the actual section. Most of the drillhole samples have been affected by the presence of open drillholes, which have not been included in the flow model.

Most of the groundwater samples from the ONKALO are from the uppermost 80 m of the bedrock. At greater depths the numbers of both samples and potential sampling locations has been small, due to the low permeability of the host rock. Most of the samples are fresh (or nearly fresh, 0.5-1.5 g/L), which is typical of shallow depths at Olkiluoto. However, the samples from the poorly transmissive ($10^{-9}$ - $10^{-8}$ m$^2$/s) fractures of ONK-PVA2 and from the leaking fractures at a depth 20-30 m are brackish (2-4.5 g/L), representing the highest values observed at similar depths. Groundwater station ONK-PVA3 is located fairly near the intersection of HZ19A and the ONKALO and the observations represent the groundwater from HZ19A and C.

The calculations showed that because the open tunnels draw groundwater from all directions from the bedrock, the excavations are likely to cause an increase in the
mixing of water types (Figure 9-46). In particular, there will be mixing of fresh and brackish groundwater from closer to the surface with deep saline waters. Following the advance of the excavations, the tunnels draw increasingly fresh water from the surface, diluting the groundwater to greater and greater depths. The magnitude of the fresh water flow is strongest along the HZs which are directly (HZ19 and HZ20) or indirectly (HZ004) connected to the tunnels. Simultaneously, the salinity of the groundwater gradually starts to rise around and below the tunnel system. The upconing of the deep, highly saline groundwater is most rapid along HZ004, which is connected to the tunnels via the HZ19 and HZ20 systems. HZ004 is a moderately-conductive zone ($T=1.3 \times 10^{-7}$ m$^2$/s), which extends from the surface down to the base of the modelled volume and offers a good hydrogeological connection between the tunnels and the deep bedrock volume with highly saline water.

Even if the inflow is limited by the grouting and the positive skin, locally the salinity may still rise to rather high levels, especially near the deepest parts of the tunnels. Whereas the previous 2006 flow model predicted only a moderate upconing at the lower characterisation level by 2015, the current flow model suggests a rise in the maximum TDS from about 21 g/L (initial value) up to 30 g/L with the calibrated baseline parameters (Figure 9-47). In the current flow model the flow porosity is based indirectly on the transmissivity data, via the cubic law, which results in about an order of magnitude lower flow porosity and a faster response of the salinity field to the excavations. The upconing will be more pronounced, if the simulations were to be continued further into the future, after the whole tunnel system has been excavated.

Due to the lack of representative TDS samples from the monitoring system and, especially, the lack of a time series of observations, it is still difficult to judge the validity of the salinity model in the presence of the tunnels. Both in the previous and current flow models, the uppermost part of the bedrock was initially (i.e. the undisturbed conditions before the excavations started) saturated with fresh water and, thus, the salinity at the shallow observation points remained unchanged in fresh water conditions during the course of the simulation (Figure 9-48). Most of the observed samples along the access tunnel (chainage of 0-700 m) are also approximately fresh, albeit the calculated ones were lower than the observations. Due to the initial fresh water conditions, neither of the flow models could capture the brackish values (2-4.5 g/L) measured from the low transmissive fractures of ONK-PVA2 and from the leaking fractures at a depth of 20-30 m.

Drillhole KR25, which is located in the vicinity of the ONKALO, provides an example of the deeper observation points available: three samples from the two different packed-off sections (Figure 9-49). The results of the 2006 flow model showed that the calculated salinity field was in practically a stagnant state at these monitoring points during the period under consideration. The combination of the hydraulic parameters controlling the evolution of the salinity field (the flow and diffusion porosities, the hydraulic conductivity and the grouting efficiency) prevented changes to the salinity, even in the closest drillholes to the tunnels (e.g. KR25, Figure 9-49). Thus, the undisturbed present-day salinity field, which was applied as an initial condition, played a major role in the predictions. However, the calculated salinity (with both flow models) agrees fairly well with the three observations in KR25, even though the number of samples is too small to allow any further conclusions to drawn. Due to the lower flow porosity, the current flow model responds more rapidly to the advance of the excavations deeper in the bedrock.
Figure 9-46. The calculated (the current flow model 2008) TDS concentration [g/L] at the vertical northwest-southeast cross-section at 2004 (undisturbed initial state before the excavations, top) and 2015 (the whole of the ONKALO has been excavated, middle and bottom). The calculations are based on the calibrated base case parameter values (middle) and on the sensitivity case (bottom), in which the parameters affecting the salt transport have been modified, so that the effect of the ONKALO would be more pronounced (i.e. the higher hydraulic conductivity of the sparsely fractured rock and lower diffusion and flow porosity were used).
Figure 9-47. The calculated maximum TDS concentration (with the previous flow model 2006 and the current flow model 2008) in the main and the lower characterization level of the ONKALO at depths of 440 and 540 m, respectively. See Figure 9-40 for the location of the characterization levels.
Figure 9-48. The calculated (the flow model 2006 and 2008) and observed TDS concentrations along the chainage of the access tunnel of the ONKALO. The calculations are based on the calibrated base case parameter values (the flow model 2006 on the top and 2008 on the middle) and on the sensitivity case (bottom, the flow model 2008), in which the parameters affecting the salt transport have been modified, so that the effect of the ONKALO would be more pronounced (i.e. the higher hydraulic conductivity of the sparsely fractured rock and lower diffusion and flow porosity were used).
Figure 9-49. The calculated (the flow model 2006 and 2008) and observed TDS concentration in the packed-off sections of drillhole KR25. The calculations are based on the calibrated base case parameter values (the flow model 2006 on the top and 2008 on the middle) and on the sensitivity case (bottom, the flow model 2008), in which the parameters affecting the salt transport have been modified so that the effect of the ONKALO would be more pronounced (i.e. the higher hydraulic conductivity of the sparsely fractured rock and lower diffusion and flow porosity were used). See Figure 9-40 for the location of the drillhole.
When simulating salt transport, the flow and diffusion porosities, which affect the time scales of transport, provided one of the sources of uncertainty and sensitivity. In the DP (dual porosity) approach applied in this study, the flow porosity affects the transport in the water-bearing fractures, whilst the diffusion porosity is related to the matrix blocks, which contain essentially stagnant water. Because of the lower seepage velocities, the higher porosities moderated the transport of solutes, so that transport occurred over a longer time scale; whereas the lower porosities induced higher velocities and a faster response to the opening of the tunnels (Figure 9-50). By the end of 2015 the maximum salinity at the lower characterisation level of the ONKALO, at a depth of 540 m, ranged between 24-44 g/L (initial value was 21 g/L) when the diffusion porosity varied between 0.2-5.0%. On the other hand, the maximum salinity was only moderately sensitive to the flow porosity, when using the applied base case diffusion porosity (1%). When the flow porosity was varied from one fifth up to five times the base case value, the maximum salinity varied from only 27-31 g/L. In the sensitivity case, in which the parameters affecting the salt transport were combined, so that the effect of the ONKALO would be more pronounced than in the aforementioned cases, the maximum TDS increased even more, up to about 55 g/L. The case was calculated using a diffusion porosity of 0.2%, a flow porosity one fifth of the baseline value and with the alternative hydraulic conductivity ($K_1$, see Table 6.2), which resulted in about 40% higher total inflow.

The calculated upconing of the deep, highly saline groundwater is fastest along HZ004, which is connected indirectly to the tunnels via the HZ19 and HZ20 systems. HZ004 is a vertical, moderately-conductive zone. It is located east of the ONKALO, extending horizontally across the island to the boundaries of the model and vertically from the surface down to the base of the modelled volume (2 km). Because the effective transmissivity of HZ004 is lower than $1.0 \times 10^{-5}$ m$^2$/s, it has also been allowed (at least until now) to intersect the disposal tunnels of the potential repository layouts. Thus, HZ004 offers a good hydraulic connection between the tunnels and the deep bedrock volume with highly saline water. The hydraulic properties and geometry of HZ004 are, however, uncertain, as they are based on only three measured transmissivities from drillholes KR8, KR28 and KR40 and indirect evidence from the geological model and from lineament interpretations. Thus, from the point of view of deep saline water upconing, HZ004 constitutes a considerable source of uncertainty.
Figure 9-50. The impact of the diffusion (top) and the flow (bottom) porosity on the maximum salinity (TDS) in the lower characterization level of the ONKALO at a depth of 540 m. In the top figure the dashed and dotted lines denote the cases, which were calculated with the lower flow porosity (fifth of the base case value). The dotted case was additionally calculated with the alternative hydraulic conductivity ($K_1$, see Table 6.2), which was higher than the base case alternative ($K_2$) and resulted in about 40% higher total inflow. The case represents the sensitivity case, in which the parameters affecting the salt transport have been modified so that the effect of the ONKALO would be more pronounced. See Figure 9-40 for the location of the characterisation level.

9.3.4 Discussion

The modelling was based on the 2008 flow model, which has been calibrated against the undisturbed baseline observations (e.g. responses from the pumping tests performed in 1992-2004, and pressure and salinity in deep drillholes). In this work the flow model was further calibrated, by adjusting the infiltration against the observed groundwater levels, as well as the transmissivity of the HZs, and also by adjusting the conductivity of the SFR around the tunnels against the observed inflows. The monitored hydraulic heads and TDS were not used in the calibration.
The results of the monitoring programme since SR2006 showed that the previous flow model clearly overestimated the hydraulic impact of the ONKALO. Having significantly more information on the inflows to the tunnel, thus allowing better calibration of the current flow model, allowed it to capture the observed inflow, groundwater level and the hydraulic heads in the deep drillholes. However, due to the lack of representative TDS samples from the monitoring system and, in particular, the lack of a time series for the observations, it was difficult to judge the validity of the salinity model in the presence of the tunnels.

Most of the drillhole TDS samples near the ONKALO are associated with intersections of HZ20A, but they were of little value for the current work, because they have been affected by the presence of open drillholes, which have not been included in the flow model. However, multi-packer systems are currently installed in the majority of the deep drillholes and, therefore, the correspondence between the hydrogeochemical data and the results of the flow simulations is likely to improve in the future.

Most of the sparse groundwater samples from the ONKALO, on the other hand, have been obtained from the single fractures (interpreted as being related to the SFR) and located in the uppermost 80 m of the bedrock and showed a considerable variation at similar depths. The 2006 and 2008 site-scale flow models are simplified, larger-scale descriptions of the bedrock. These single fractures have not been considered in the flow models explicitly, but have been included implicitly in the effective hydraulic conductivity, which is based on the geometric means of the transmissivities measured from the small-scale fractures. The resulting conductivity was not spatially variable, but changed only with depth throughout the modelled volume (in a similar manner to the flow porosity, which was linked to the conductivity by the cubic law).

The diffusion porosity, another parameter affecting the salt transport, was assumed to be constant throughout the modelled volume. Initial conditions for the baseline simulations were also not spatially variable, but changed only as a function of depth throughout the modelled volume. Thus, with the HZs constituting practically the only heterogeneity in the flow model, it is not possible to capture all the observations originating from the smaller-scale features, especially when they show considerable variation at similar depths, such as the TDS data from the ONKALO.

9.4 The EDZ

9.4.1 Introduction

The excavation damaged zone (EDZ) can have an impact on the long-term safety, because it can change the fluxes and the flow paths and, consequently, have an influence on the performance of the engineered barriers, as well as on the transport of radionuclides and other substances.

Changes in the rock properties within the EDZ, which may affect the long-term safety of a spent nuclear repository, include (NEA 2002):

- Reactivation of existing fractures, and the formation of new fractures,
- Changes in porosity, which can be several orders of magnitude compared with the undisturbed rock
• Chemical changes, especially during the operational phase when there are open
tunnels and the backfill and buffer are unsaturated, but potentially also later.

An R&D programme, known as the EDZ programme, was launched by Posiva to
enhance understanding of the characteristics of the EDZ, its evolutionary mechanisms
and its behaviour as a groundwater flow path. The programme consists of three sub-
projects: Excavation Management, Verification and Magnitude of the EDZ. The tasks of
the programme are described below.

The objectives of the programme were specified as follows:

• Development of verification methods for characterising the EDZ,
• Development of excavation methods for control of the EDZ,
• Assessment of the significance of the EDZ as a pathway for groundwater flow
  and transport and
• Development of methods to eliminate or mitigate the impact of the EDZ to an
  acceptable level.

The programme was implemented as a joint effort of the Research, Engineering, and
Project Departments, and included the activities of sampling, testing and research and
other field tests in the ONKALO; although its execution was the sole responsibility of
the ONKALO Project. The VARTU and OMO Programmes were at the EDZ
Programme's disposal to provide initial data about rock properties in the Olkiluoto area.

The sub-project “Excavation Management” is focusing on the second and fourth tasks
listed above. Mitigating the impact of the EDZ can be carried out by, for example,
optimisation the drilling and charging plans.

The sub-project “Magnitude of the EDZ” focussed on the impact of the EDZ on long-
term safety, and included estimating the potential impact of the EDZ on flow rates
within the repository volume, transport routes and transport resistance. In the
calculations, the flow model used was that presented in Site Description 2006
(Andersson et al. 2007) and the DFN model that of Poteri & Löfman (2008). The EDZ
was assumed to be continuous and to have a thickness of 50 cm along the tunnel wall
and roof and 1 m below the tunnel floor. The hydraulic conductivity of the EDZ was
varied from 100 to 1000 times that of the rock mass and the hydraulic conductivity of
the buffer was assumed to be equal to that of the rock. The assumption was that the
hydraulic conductivity of the EDZ at the repository depth was in the order of 1E-8 - 1E-
7 m/s, the values being at the higher end of the values reported in the literature for the
conductivity of the EDZ in crystalline rock (e.g. Emsley et al. 1997, Pusch et al. 2004).
Different options of limiting the EDZ to certain tunnel sections were studied. According
to the results, the EDZ has only a minor impact on groundwater flow rates at the
repository depth, on transport routes and on transport resistance. The modelling
approach, the results and the related uncertainties are further discussed by Mellanen et
al. (2008).

The studies related to characterising EDZ have been focused on testing different
investigation techniques for its verification and characterisation, as well as for Quality
Control purposes. The significant parameters to be measured and which determine the
scope of the investigations are: the continuity, thickness and conductivity of the EDZ.
The main methods used in these studies were:
The methods used during the EDZ programme, as well as the methods used earlier in EDZ studies, are reported, for example, by Saukkonen (2008), Silvast & Wiljanen (2008), Vuokko et al. 2008 (see also Table 2-8 in Section 2.6.2); with these studies being used as background material in compiling the final report of the EDZ programme (Mellanen et al. 2008). The work included in the Verification sub-project was mainly pilot testing, with the objective of selecting the most feasible methods for characterising the EDZ.

9.4.2 Extent of the EDZ

The scope of the EDZ studies before the start of the EDZ Programme was focused solely on determining the “thickness” of the EDZ. This was due to the approach taken to control the EDZ at the beginning of the construction of ONKALO access tunnel; with the EDZ being conceptualised in terms of an increased fracture intensity in the excavated tunnel’s walls and floor. Two drilling campaigns were conducted to study the thickness of the EDZ in 2005 and 2006, see Figure 9-51.

The parameters related to the extent of the EDZ are its thickness and continuity and these parameters were studied in the EDZ programme. The third drilling campaign (Figure 9-51) was conducted in a similar manner to the two previous campaigns. 24 drillholes were drilled into the floor in the ONKALO access tunnel in the chainage intervals 1956-1985 m and 2439-2453 m; the tunnel sections being selected to include “normal” blast rounds, as well as blast rounds where different excavation techniques had been tested. The third drilling campaign, together with the two earlier campaigns, are reported in Vuokko et al. (2008).

The purpose of obtaining block samples by sawing was to investigate the effect of blasting on rock properties and to compare EDZ-induced fractures with those of a natural origin. Nine rock block samples were extracted by sawing in 2007. The samples EDZB5-EDZB7 were extracted from the access tunnel floor, but two of these samples were broken and rejected. These three samples from the floor were extracted from blast rounds where non-digital detonation was used (Mellanen et al. 2008, Appendices 3 and 4). Figure 9-52 presents the only unbroken sample from the floor at chainage 2080 m. Some of the holes included in the third drilling campaign were drilled in the same locations in the access tunnel as where the rock blocks were extracted, see Table 2-8 in Section 2.6.2. The cores have been studied and compared with the results gained from the extracted samples (Vuokko et al. 2008).
Ground Penetrating Radar (GPR) measurements have been performed with 3 different GPR systems (Figure 9-53). The time range for the antennas was set between 15-115 ns, depending on the antenna frequency. Data collection was controlled by a calibrated digital measurement instrument (survey wheel), which was attached either to the measurement car wheel or to the wire distance measurement box. The scans were collected at 1-5 cm horizontal intervals, depending on the measurement system. During the measurements chainages were related to the GPR data using digital markings. A digital video of the wall surface was also collected at the same time from some of the GPR survey lines.
In the pilot study (Silvast & Wiljanen, 2008) several different GPR measurement configurations were tested and the results proved that GPR is a potential tool for quick, non-destructive surveys of bedrock structures and properties. The use of ground-coupled 1500 MHz GPR in detecting the EDZ also proved to be promising. Information from the GPR data can be used to distinguish changes in electrical conductivity of the bedrock and in finding fractures.

Multi-channel, stepped-frequency 3D-GPR provided similar results as ground-coupled 1500 MHz GPR. The 3DGPR data present fractures as more continuous reflectors, due to the different measurement geometry. The results from the shaft measurements proved to be different from the tunnel wall measurements using the same GPR system with respect to the signal dispersion profiles. Differences in excavation methods or changes in rock types can cause these variations. Air-coupled, high frequency GPR antennas are efficient in analysing the EDZ. 1 GHz and 2.2 GHz antennas both gave clear data, with the 2.2 GHz data having a better resolution. Figure 9-54 presents the results from the longitudinal GPR profile in chainage interval 2445-2455 m at a height of 2.0 m from the floor, with a GSSI 1500 MHz antenna and a dispersion profile from the same data showing high frequency attenuation. The lowest part shows the interpreted EDZ, which varies in thickness from 0.3-0.5 m, when using a dielectric value of 7 in the calculations. The work with GPR continues with, for example, verification of the interpreted depths of the EDZ.
Figure 9-54. Longitudinal GPR profile (chainage interval 2445-2455 m/left wall) at a height of 2.0 m from the floor, with a GSSI 1500 MHz antenna, and a dispersion profile from the same data showing high frequency attenuation. The lowest profile is the interpretation with true depths calculated with a dielectric value of 7 (Silvast & Wiljanen 2008).

Vibration measurements were used to examine the excavation process, the vibration conductivity of the rock mass in the tunnel, and to estimate the size of the EDZ due to excavation. The homogeneity of the rock was examined by means of vibration conductivity; with the results of this study concluding that the rock mass between the sensors was, as a rule, quite solid, thereby indicating a small EDZ.

According to Saukkonen (2008), cracking of rock occurs when the vibration velocity exceeds a threshold value of 700 mm/s. The cracking distance (the distance from a blasting hole with a specific charge, i.e. the amount of explosives, kg/m, causing cracking of rock due to the vibration velocity being higher than the above-mentioned threshold value) was estimated at different certainty levels. These certainty levels were obtained by making measurements at a considerable distance from the blast face, with the result that the vibration velocity of each blast hole could not be determined (the detonation was assumed to be in the centre of the tunnel profile) – and for this and other reasons, which are explained in Saukkonen (2008), there is considerable uncertainty in the estimated volumes of damaged rock. The results of this study indicated that at a certainty level of 98% the velocity value of 700 mm/s will not be exceeded at a distance of 3.4 m from the centre of the drift. The distance from the centre of the ONKALO tunnel to its walls is about 2.75 m and about 3.45 m to its floor and ceiling; therefore the cracking zone is estimated to be about 0.55 m from the wall into the rock, but barely noticeable in the floor and the ceiling.
The vibration measurement results of Saukkonen (2008) were compared with the initial excavation data (the drilling and charging logs) and with visual observations of the tunnel walls and ceiling. Results from the scaled distance curves in the direct surroundings of the blast round are quite uncertain and the considerable distances from the measured area (50-110 m) also introduce uncertainties. Considering these uncertainties and the calculated cracking distances, the results representing the cracking zone in the wall can only be regarded as a rough estimate of the dimensions of the EDZ.

Work by Vuolio (1991), which is extensively quoted in Saukkonen (2008), shows the relationship between the charge and volume of the explosives and the expected cracking distance for a single blast hole. The expected damage distance from this relationship is similar to that determined by Saukkonen (2008).

Measurements on the same survey profiles would allow a comparison of the EDZ depths obtained using different methods, thereby increasing confidence in the results. In this phase the investigations were mostly carried out at different locations in the ONKALO access tunnel, as shown in Table 2-8 (Section 2.6.2), and the focus was on testing different methods; however, some values of the EDZ parameters (thickness, continuity and conductivity) were obtained. These results must be considered as preliminary, due to the fact that some EDZ interpretations (e.g. GPR) need further study before the results can be confirmed. Also the number of samples is too limited to draw any reliable conclusions. The preliminary interpretations from the access tunnel walls from GPR are in line with the assumed thickness values for the EDZ, lying mainly in range 0.3...0.4 m. There are indications in the GPR dispersion profiles that the depth extent of the EDZ varies within a blast round, with the widest EDZ values being located where bottom charges have been used. GPR was the only tested method which could be used for estimating the continuity of the EDZ, due to the continuous nature of the survey. Although the thickness of the interpreted EDZ varies along the survey profiles, the EDZ could be considered as being continuous, if the interpretation were based solely on GPR results. The hydraulic conductivity of the EDZ was measured using small-scale water loss measurements in four short (c. 0.4 m long) holes drilled on the access tunnel wall, suggesting that the hydraulic conductivity of the EDZ can be very low; which could suggest that, although the EDZ might be continuous in a physical sense, it may not be continuous hydraulically.

Fractures in the sampled blocks extracted from the floor and the walls of the ONKALO access tunnel and from tunnel niches appear to have been almost entirely induced by the blasting process (referred as EDZ fractures or EDZ-type fractures) - with no mineral coatings or veins being observed on fracture surfaces. The EDZ fractures typically have a depth extent of only 0.2-0.3 m, and do not penetrate deeper into the surrounding intact rock. The only unbroken sample that was extracted from the floor was sample EDZB7 (Figure 10-3). The block contains numerous fractures and fracture arrays sub-parallel to the trends of drillholes, the longest being more than a metre in length; although more typically they are in the range 0.3-0.4 m. Although the length of some fractures exceeds the width of the block, none were seen to continue from the sample into the surrounding rock. The EDZ-type fractures are considerably more abundant in the pegmatitic granite than in the mica gneiss, although the longest fractures (about 0.8 and 0.4 m, respectively) transect both rock types. The fractures initiated during excavation tend to be 0.1 – 0.4 m in length.

The results obtained from the second and third drilling campaigns (Figure 9-51) indicate that the depth extent of the zone of increased fracturing is approximately one metre
from the tunnel surface. This indicates a slightly higher thickness of the EDZ compared with the target values of 0.8 m in the floor and 0.4 m in the walls. However, the majority of the EDZ fractures occur from 0-0.4 m depth (54-64% in the third campaign). In the tunnel profile at chainage 790 m during the second drilling campaign 22 samples, divided between the floor and two walls, were core drilled. In this tunnel profile the depth of the EDZ is approximately the same, c. 0.4 m below the floor and in the walls. The results, however, must be regarded only as indicative, because of the limited number of samples. It is also likely that any fracturing caused by core handling (e.g. during removal of the sample from the core barrel) has not been identified and that such fractures are included in the total. It is also possible that the division of non-natural fractures into: a) natural, healed fracture opened by the excavation process, b) new EDZ fractures and c) possible new EDZ fractures caused by excavation or by core sampling, may itself be uncertain. Some of the blast-induced fracturing is evidently natural fracturing, which has been deformed and opened by blasting; however, is it very difficult to detect such fractures with confidence (Vuokko et al. 2008).

9.4.3 Properties of the EDZ

One of the objectives of the EDZ programme was to develop methods for characterising the EDZ as a conduit for groundwater, instead of only its “thickness”.

The conductivity of the EDZ was tested with a small-scale Water Loss Measurement pilot test that was conducted in the ONKALO access tunnel (Figure 9-55). The drilling of the short, c. 0.40 m long, drillholes (6 drillholes, diameter 32 mm) was made with a light drilling unit.

The equipment was tested and was found to work as planned. The highest pressure value tested was 10 bars and anchoring of the packer was found to be a requirement, even at low pressures. The pressure was found to be stable, even during the longest measuring period of 67 hours.

The interpreted transmissivity values from the small-scale, water loss measurement pilot test are presented in Table 9-11. Drillholes 2 and 6 were rejected due to leakage into the tunnel (hole 2) and due to an open fracture along drillhole 6, which affected the tightness of the measuring section. The measured transmissivities were lower than expected. The number of drillholes and test sections was, however, limited and more hydraulic measurements are needed to characterise the hydraulic conductivity of the EDZ with a greater level of confidence.

The EDZ along the ONKALO could have an impact on long-term safety, due to the increased flow of surface and near-surface waters to greater depths, which could disturb the geochemical stability of a future repository. Changes in sorption and related hydrogeochemical properties are possible during the operational stage (e.g. open tunnels, unsaturated repository phase) but also later. To date, however, geochemical changes caused by the EDZ have not been studied in the ONKALO.
Table 9-11. Transmissivity values from the small-scale water loss measurements, variables were: duration of test and injection pressure. The results can be considered only as preliminary. Test sections were kept constant in each drillhole.

<table>
<thead>
<tr>
<th>Drillhole</th>
<th>Measurement 1 T (m²/s)</th>
<th>Measurement 2 T (m²/s)</th>
<th>Measurement 3 T (m²/s)</th>
<th>Measurement 4 T (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drillhole 1</td>
<td>5.4 E-11</td>
<td>4.5 E-11</td>
<td>3.2 E-11</td>
<td>6.2 E-11</td>
</tr>
<tr>
<td>Drillhole 3</td>
<td>2.6 E-11</td>
<td>2.3 E-11</td>
<td>2.1 E-11</td>
<td>9.8 E-11</td>
</tr>
<tr>
<td>Drillhole 4</td>
<td>4.4 E-12</td>
<td>4.3 E-12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drillhole 5</td>
<td>2.6 E-12</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 9-55. The equipment used in the pilot test of the small-scale water loss measurement (Mellanen et al. 2008).

The results obtained during the pilot test phase of the Verification sub-project indicate that the parameter values describing the EDZ used in the models seem to agree with the observed results reasonably well. There are still some uncertainties associated with some of the methods, e.g. GPR, which, therefore, need further development before they could become validated methods for characterising the EDZ. Also there are some indications from the drilling campaigns that some non-natural fractures, induced possibly by the excavation process, extend to greater depths into the surrounding rock.
than the values used in the models. The hydraulic conductivity values obtained during the pilot testing of small-scale water loss tests in a few short drillholes indicate lower transmissivities than used in the models.

9.4.4 Further Plans for EDZ studies

Posiva is planning to excavate investigation niches in the ONKALO access tunnel during 2009, with one of the niches being planned to focus on EDZ-related issues. In order to allow comparisons to take place between the different investigation methods, they will be carried out over similar volumes of rock within the niche, i.e. along the same profiles or using the same drillholes. The studies are planned to be performed in two phases, prior to the excavation of the niche and after its excavation, in order to detect the changes (i.e. EDZ formation) caused by the excavation process. Tomographic methods (e.g. borehole radar, electrical resistance, seismic) between drillholes or between the tunnel surface and a drillhole are potential methods to be used in these studies.

In order to ensure that the best results are obtained, a comprehensive investigation plan will be compiled prior to the studies and the excavation of the niche. The investigation plan will include, for example, a description of the methods and how they are planned to target the most significant characteristics of the EDZ, and descriptions of how the results of the tests will provide information on the properties of the EDZ. The hydraulic conductivity of EDZ will be the crucial issue in these future studies, and its continuity and thickness will also be further studied.

The GPR method has proved to be promising and, in the future, further tests with reference measurements will be carried out, with the objective of calibrating and validating the GPR interpretations of the EDZ.
10 OVERALL CONSISTENCY AND CONFIDENCE ASSESSMENT

This chapter assesses the overall consistency and confidence in the Site Model 2008 and focuses on discussing the main issues of importance that are judged to require further attention. A more formal audit check is also presented, concerning aspects of uncertainty, the handling of data, the need for alternatives and interdisciplinary consistency, and concludes with an overall assessment of the confidence in the model. The input has been compiled based on a series of special cross-disciplinary workshops. The specific questions addressed at these workshops, as well as the detailed findings, are documented in full in Appendix 10.

10.1 Introduction

There are uncertainties associated with the Site Descriptive Modelling and it is necessary to assess its confidence. Site Report 2006 (referred to as SR2006, Andersson et al. 2007) assessed this by applying a set of protocols, which were first addressed by the discipline experts and then discussed and revised in a series of cross-discipline workshops. A similar procedure, using protocols and workshops, has been followed during the development of Site Report 2008 (referred to as SR2008), although the protocols have been modified slightly from those employed in SR2006. The protocols are concerned with the following matters:

- How SR2008 addresses the needs of the safety case, see Table 10-1 in Appendix 10.
- The main issues in SR2008, relating to the confidence and uncertainty of the site model and of concern for repository construction and long-term safety, see Table 10-2 in Appendix 10.
- Data support, confidence and uncertainty in the resulting SDM input to the safety case, see Appendix 10-3,
- The potential for alternative interpretations, see Appendix 10-4,
- The level of consistency between disciplines and the consistency with regard to understanding the past evolution of the site, see Appendix 10-5 and
- Comparisons with previous model versions, see Appendix 10-6.

The results of this assessment are provided in Tables 10-1 to 10-6 in Appendix 10 and a summary of the main findings is given below.

10.2 Addressing the needs of the Safety Case

Before considering the confidence and uncertainties in the site description, it is important to consider the elements of the site description that are considered necessary for the development of the Safety Case. These can be derived from the overall safety functions of the geosphere, the rock properties which contribute to the fulfilment of the safety functions and the processes affecting these properties. The safety functions of the geosphere are defined to be (Posiva 2003, Posiva 2006, Vieno & Ikonen 2005 and recently Posiva 2008):
• to isolate the repository from the biosphere and normal human habitat;
• to provide favourable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers and to protect them from potentially detrimental processes taking place above and near the ground surface and
• to limit and retard inflow and release of harmful substances to and from the repository.

The site description should provide the information (both process understanding and data) needed for the conceptualisation and modelling of the processes affecting the safety functions. Miller & Marcos (2007) provide a summary of the processes affecting the evolution of the site and the repository and the migration of radionuclides and other substances.

The rock properties and their value range defining the conditions that contribute to the fulfilment of the safety functions of the geosphere, are currently being developed. Practical criteria (Rock suitability criteria, RSC) to select rock volumes that are likely to provide the desired rock properties in the long term, and are thus suitable for hosting deposition holes, are being developed within the rock suitability criteria (RSC) programme. According to the Safety Case Plan (Posiva 2008), the models and data used for describing the evolution of the site and the repository and the safety assessment will be summarised in what are known as the Models and Data Reports. These reports will include discussions of the uncertainties and the abstractions and simplifications needed and their impact on the results of the safety assessment. The first such Models and Data Report will be published in 2009 and the second in 2012, with the first concentrating on data used in the recent safety assessments (for KBS-3H, Smith & al. 2008, and for KBS-3V, Nykyri et al. 2008). The site description provides important inputs for these and other Safety Case reports.

The Safety Case needs of the site description have been discussed between members of Posiva’s safety case group (SAFCA) and the OMTF. Table 10-1 in Appendix 10 lists the information the Safety Case is expecting from the Site Description, indicates whether this information is provided by SR2008, and, if not, indicates the other reports that should provide the data. These information requirements of the Safety Case are as follows:

• **Groundwater composition:** groundwater composition in the near-field and processes affecting the groundwater composition (salinity – chloride, pH and alkalinity, ionic strength, sulphate and sulphide concentrations, redox environment, concentration of K⁺, gases, colloid concentration, organics, microbes, phosphates and nitrogen compounds, especially nitrates and ammonia), rock and fracture mineral geochemistry.

• **Deformation zones and fracturing:** Deformation zones and fracturing (geometry, orientation, size, intensity, spatial structure, mineralogy of infills and fracture coatings, mechanical, hydraulic and retention properties).

• **Flow-related properties:** groundwater flow at the site and at the more detailed scale, necessary for assessing flow around deposition holes (flow and transport paths, geometry, flow rates, release points, discharge areas) and boundary conditions.
• **Migration properties:** flow-related migration properties (flow rates, transport resistance WL/Q, retention model, advective travel times), matrix-related migration properties (porosity, effective diffusion, distribution coefficients).

• **Rock mechanics:** stress state, rock strength and deformation properties.

• **Thermal properties:** initial temperature, thermal conductivity, thermal diffusivity, heat capacity, regional heat flow.

• **Impacts from underground construction:** EDZ (its extent and hydraulic properties), thermally-induced spalling, inflows, construction-related materials, stress state changes, chemical changes (grouting cement, pH).

• **Site Synthesis:** demonstration of overall site understanding; process understanding (groundwater flow evolution, evidence of slow transport in the geosphere, reducing conditions, salinity evolution, sulphate reduction and microbial processes, gas generation and rate of gas transport, features contributing to retention and retardation of radionuclides, stable rock mechanics conditions), predictability (bedrock conditions, groundwater conditions and resulting chemical conditions).

SR2008 provides most of the input data needed, or at least provides the basis for further assessing process understanding in the Safety Case (Table 10-1). It is noted that the Site model discusses the current and past conditions of the site and the impact of the construction of the ONKALO. The future evolution of the site and the repository and radionuclide transport will be covered by reports produced according to the Safety Case Plan (Posiva 2008). The main reports, in addition to the Models and Data report, are: Description of the Disposal System, Process, Formulation of Scenarios (including repository evolution), Analyses of Scenarios (including radionuclide transport calculations), Complementary Considerations, and Summary Report.

### 10.3 Main issues concerning the 2008 Site Model

In a similar manner to that of SR2006, a part of the site modelling presented in SR2008 has been to explore the extent of confidence and the remaining uncertainties, if any, within the different subject areas. Generally, the mass of information available allows an elaborate and, at least in the ONKALO volume, very detailed description of the site, but some issues still remain which are considered to require further attention. The following questions have been addressed:

- Discussing the status of issues identified in SR2006 and, where applicable, identifying additional, remaining issues.

- Why a particular issue is important – reference to Table 10-1 in Appendix 10.

- Explain why a particular aspect of the site is an issue, i.e. cause of uncertainty, or, if the issue is thought to be close to resolution, the reason(s) to be confident.

- Where the issue is discussed in SR2008

- Discussion on the need and type of further actions (e.g. need for more data or modelling activities).
The findings of these evaluations are discussed in the following subsections. The complete answers are listed in Table 10-2 of Appendix 10.

10.3.1 Geology/hydrogeology issues

II: Character of the rock mass in the potential repository volumes

The character of the rock mass in the potential repository volume, i.e. the rock volume below HZ20 (Hydrogeological Zone 20), see Chapter 6, is of course of primary importance, since this directly relates to the suitability of the site for disposal and overall understanding of the site. There is good data coverage, allowing the identification of all layout-determining features, in all potential repository volumes, except in the eastern part of Olkiluoto Island, where there are yet few drillholes. This eastern part is potentially important, since it may need to be used for an extension to the repository, if the amount of the waste to be disposed off increases.

As discussed in Chapters 4 to 6, there is a high level of confidence in the description of the ONKALO volume. The data density is high and the fair agreement between predictions and outcomes encourages this confidence (see Chapter 9).

- The data from the central part of the island (i.e. where ONKALO and most of the current drillholes are located) strongly suggests that there are very few highly transmissive features outside the gently-dipping hydrogeological zones. A consistent picture has been developed that the main transmissive features are confined to the HZ19, HZ20 and HZ21 zones.

- Based on observations from the ONKALO, subvertical faults have been observed, but would be hard to detect with the orientations of the existing investigation drillholes. However, these vertical features are likely to be much less transmissive than the gently-dipping HZs. So far, very few transmissive subvertical features have been found in the ONKALO, but there is a need to have more data from the ONKALO below HZ20, i.e. in more representative rock, before any more definite conclusion can be drawn. Furthermore, the subvertical features may be important from a mechanical point of view, even if they are not transmissive.

As already stated, there are considerably fewer data from the eastern part of the island:

- Three-dimensional seismic data suggest that many aspects of the central part of the island, like the three gently-dipping HZs, can be extrapolated to the east. However, the seismics, as well as surface, and magnetic data in the east, show the existence of subvertical features, off-setting these gently-dipping zones. These subvertical features are thought to be related to the Rapakivi granite intrusions and are not encountered in the central part of the island; thus complicating any extrapolation to the east.

- The locations of these subvertical features have been fairly well established from the geophysics data, but details of their character or their extent are unknown. Also the hydrogeological data from drillholes OL-KR11 and OL-KR45 suggest that the eastern part of the island is different.
The frequency of transmissive features in the eastern area appears to be as low as in the rock lying between the hydrogeological zones in the central part of the island. However, this conclusion is based on few data and there are no hydraulic data from the subvertical features.

In order to enhance confidence of the eastern area a few more drillholes, possibly complemented by detailed magnetic surveys, would be useful. Such drillholes are planned for 2009 and beyond.

**I2: Can we characterise the disposal volume in sufficient detail to allow reliable decisions to be made on the locations of disposal tunnels and deposition holes?**

At the detailed scale there may be features, which are not possible to detect from existing surface-based drillholes, from the ONKALO or from characterisation holes from the ONKALO area. The question is, therefore, if current tools for tunnel observations and predictions of the surrounding rock mass are sufficient to characterise the necessary structures.

The reasonable agreement between predictions and outcomes, see Chapter 9, on key aspects regarding the layout of the repository, such as the potential for intersecting layout-determining features, the level of fracturing, the geomechanical conditions and the inflows, demonstrates that we can characterise a volume in sufficient detail, when the underground excavations are close to the volume being investigated, to allow decisions on the detailed locations of disposal tunnels.

Furthermore there are now sufficient data to characterise the potential layout-determining features close to the ONKALO, allowing decisions to be made on the locations of the first disposal panels. There is still an issue, however, regarding the stress levels and stress orientations, as they are still uncertain (see issue I6). Data from below HZ20, especially regarding rock stress, would, therefore, be needed for determining the orientation and detailed design of these panels. Generally, it is judged that there is sufficient capacity to characterise the rock to the necessary level of detail. The RSC programme is, however, still establishing what data will be needed for allowing a decision to be accepted regarding the location and orientation of a deposition tunnel and, similarly, for accepting a decision on the location of a deposition hole. Questions remain regarding the details of the data that would be required to allow such decisions to be officially accepted, and how to make most efficient use of site understanding in this regard. More consideration needs also to be given as to when data need to be available for influencing such decisions.

In order to resolve this issue, a focused characterisation programme below HZ20 is planned, including a large coverage of pilot holes. The possibility of more detailed exploration activities, e.g. using several pilot holes in one section, could possibly be studied using investigation niches.

**I3: Geological Understanding of the Deformation History**

A proper Deformation History model, see Chapter 4, should be able to explain the current observations and enhance confidence in the conceptual model. The lithological evolution and the ductile deformation history were already rather well understood in SR2006; and since SR2006 there have also been advances in the understanding of the brittle deformation evolution. There has also been an extensive discussion with the
hydrogeology team on the understanding of deformation zones. Some uncertainties remain:

- There are still some uncertainties related to the association of brittle deformation and the Rapakivi formation to the east (see issue I1).

- It is not yet firmly established whether brittle deformation zones exist within which there has been no faulting (i.e. joint zones).

A conceptual model now exists, but it should be further developed in such a way that the modelled features can be constrained in a more rigorous manner (extent, age relationships etc.). Also, even more use could be made of the ONKALO data, assessing them in more detail, in combination with regional geological data. $^{40}\text{Ar}/^{39}\text{Ar}$ studies have been initiated - these could provide information on the different cooling ages of the blocks and thus on the potential for brittle deformation without faulting.

**I4: Connectivity and transmissivity of fracture networks at the site – especially in the potential repository volume**

Connectivity and transmissivity are important for predicting the flow distribution in the repository (both for open and closed conditions) and for estimating retention along flow paths. Generally, there is a quite high level of confidence in the knowledge of these properties, see Chapter 6:

- The Posiva Flow Log (PFL) primarily measures the connected transmissive features. There are a lot of such detailed hydraulic data from the ONKALO. The data show that only a few features in drillholes have connected transmissivities greater than $10^{-9}$ m$^2$/s.

- The Hydrogeological DFN model describes the transmissive fractures between the deterministic HZs. The hydrogeological DFN is consistent with existing data.

- There is generally a good level of confidence in the overall hydrostructure model. The SR2006 model has been largely confirmed by the observations made during the excavation of the ONKALO.

However, some uncertainties remain:

- There are more uncertainties in the eastern part of the island (see I1 above).

- At the large scale, the data show very sparse hydraulic connections, but there could possibly be more, very local hydraulic connections between closely-spaced drillholes. Such connections do not persist over greater distances. The existing PFL data provide a very good control on the connected fractures, but not on the non-connected, but potentially transmissive fractures. Indirect information on potential local hydraulic connections exist, e.g. from drillhole imaging and core logging, but these data generally overestimate the frequency of such features. Direct information on the latter would require small-scale underground interference tests, i.e. made at a scale where these naturally “isolated” fractures would connect between the induced disturbance and the measurement points. The pressure responses from tunnel construction could also be an indirect source of information on these features. This uncertainty is, at least partly, handled by formulating different alternative
hydrogeological DFN models, with different assumptions regarding the frequency of
the water-conductive fractures (and the resulting fracture size distribution).

- There is no clear conceptual understanding as to whether only certain fractures are
  hydraulically important (and then what their characteristics are), due to internal
  variations in the fracture or due to the poor connectivity of the fracture network. It is
  probably a combination of both. At any rate, since the densities of isolated inflow
  points on the ONKALO tunnels are not notably higher than the expected density of
  connected transmissive fractures, at least the majority of the flow cannot be
  concentrated within distinct isolated “worm-like” channels. Furthermore, the impact
  of channelling on the resulting migration properties can be bounded, see e.g.
  Crawford (2008).

Updated DFN analyses of existing and new hydraulic data from the ONKALO will
further enhance confidence. Numerical flow modelling could assess the resulting
connectivity for different representations of the fracture network. An interference test
executed at depth, e.g. in an investigation niche, should be considered. Shedding light
on this issue would build on a careful detection of the groundwater flow in the drillholes
employed in the interference test, as well as on a careful geological characterisation of
the fractures intersecting the drillholes. In the course of the experiment, water will be
pumped out of or into each drillhole, whilst pressure and flow rate responses are
measured in the other drillholes. The analysis of experiments needs to be supported with
numerical flow modelling.

15: Integration between the hydrogeological and geological models - utilisation of
hydrogeological data in the construction of the flow model

Consistency between the disciplines of geology and hydrogeology is essential for
overall understanding, however, it must also be understood that all features of the
groundwater model may not be hydraulically important.

As shown in Chapter 6, the SR2008 large-scale hydrostructure model is now basically
consistent with the SR2008 geological model. The changes since SR2006 mainly
concern revisions to the geological model, that now also incorporates the information
provided by the geophysical data, and do not rely exclusively on strict rules on how
faults observed in different drillholes should be connected (which was the situation in
SR2006). As part of the interactions between the geological and hydrogeological teams,
some modifications have also been made to the details of the hydrostructure model.

The few remaining differences essentially concern areas where the level of confidence
is still poor in both models (e.g. in the eastern part of the island, see issue I1). Also, the
groundwater data suggest larger-scale connections than are actually observed
hydraulically, although this does not necessarily mean that these connections do not
exist. The geological model also includes small-scale features that have been shown to
be hydraulically insignificant. These differences should be no surprise, since the
groundwater properties of geological features vary in space, i.e. we must expect that some
groundwater features should not be hydraulically significant, at least not over their entire
areas or volumes.

The established interaction between the geological and hydrogeological teams will
continue.
10.3.2 Rock Mechanics and thermal issues

I6: Stress distribution and orientation in relation to the geological structures

The stress magnitude and orientation is needed for the safety case. The stress model is assessed in Chapter 5.

In SR2006 it was noted that a full understanding of the details of the stress distribution was unavailable and that the spread and uncertainty in existing rock stress measurements was large. Furthermore, the stress would be affected by the geometry of the geological structures, the mechanical properties of the rock and the stress history. This could also locally affect (i.e. rotate) stress orientations (of potential importance for the orientation of deposition tunnels).

Since SR2006, a limited number of new data have been obtained, including convergence measurements, new in situ stress data from OC (overcoring), compilation of all CD (core discing) observations, strain measurements in the ventilation shaft and observations from the ONKALO tunnels. A semi-integrated stress analysis was also carried out (Ask, expected 2009). The analysis included all stress data that were considered of good quality. The following can be noted:

- The new stress measurements using OC at the –230 m level still had problems with the glue – and the measured stress orientations add to the scatter of the already existing OC data.

- The convergence and strain measurements at the -180 m level suggest that the orientation of the maximum horizontal stress above -300 m is N-S, rather than the commonly-seen E-W…NW-SE regional orientation; but the stress field may rotate back to this regional orientation below -300 m.

- ONKALO observations show some occurrences of potential stress-induced failures, but these could also be associated with blast damage and geological structures (i.e. the presence of fractures or a well-developed foliation).

In conclusion, above – 300 m the orientations of the maximum horizontal stress seem to be locally N-S and below – 300 m locally E-W (rather than the generally regional plate tectonics orientation of NW-SE in Finland), possibly due to the relaxation of the stress field above this depth. Below – 300 m, the upper bound of the stress is uncertain, and may be different from that indicated by the current stress data.

Some hydraulic fracturing (HF) data in OL-KR40 and in one ONKALO shaft grouting hole and some acoustic televiewer measurements in OL-KR19, OL-KR40 and OL-KR46, carried out to study borehole breakouts, will be available at the end of 2008. Studying the presence/absence of borehole breakouts could provide some bounding estimates to the stress magnitude. A more definite understanding of the stress will be obtained from the rock mechanics shaft response tests planned below – 300 m and from the further observations in the ONKALO. Given the practical difficulties, there is possibly little use in carrying out further drillhole OC tests, but this possibility will still be considered, if the experimental problems can be resolved. The link between the geological structures and the local stress state on Olkiluoto Island may be assessed by further modelling. This work will start in 2009.
I7: Properties of intact rock

Intact rock strengths and related properties are needed for the Safety Case. These properties are assessed in Chapter 5.

As already stated in SR2006, there is a good understanding of the distribution of these properties. The anisotropic strength and deformation characteristics of the rock are quite well understood and, based admittedly on only a few tests, it has been observed that the altered rock may be as strong as unaltered rock. The lithological model appears to be sufficient for judging the distribution of properties in the potential repository volume; however, some uncertainties remain:

- There may still be some uncertainties regarding the eastern part of the island (see issue I1).
- Spalling strength data at the necessary scale are currently still based on experience from the Äspö HRL and other URLs, not on site-specific tests.
- Long-term strength properties are generic and based on extrapolation from tests carried out on rock samples in different laboratories throughout the world.

In order to reduce uncertainty, in situ experiments, similar to the ones SKB now conducts at Äspö, are planned for below HZ20, where they would be directly relevant to conditions at the repository panels. ONKALO tunnel observations and monitoring will provide further information on the long-term mechanical properties.

I8: Mechanical properties of the brittle deformation zones (BDZs)

The mechanical properties of the brittle deformation zones at Olkiluoto are required for rock mechanics numerical modelling, see Chapter 5. Brittle deformation zones represent major weaknesses in the rock mass continuum and their preferential southeasterly dip at Olkiluoto will have a major effect on rock mechanics analyses (although not so much in the near-field analyses, since such structures are avoided in locating the deposition tunnels, but important in the far field/stress modelling analyses to understand the in situ stress conditions at the site). This could potentially affect the design of the repository, in the event that these properties are shown to be important in controlling the stress field.

There is good geological knowledge of the location and geometry of the brittle deformation zones at Olkiluoto, and an initial estimate of their mechanical properties has been achieved via the use of rock mass classification. A report (Hudson et al. 2008) has been prepared by the Rock Mechanics OMTF group on a rock mechanics characterisation methodology for the brittle deformation zones. The existing data consist of photos of all the core BDZ intersections in the drillholes, the geological descriptions of these, the Q classification logging data of the cores and Q logging data from tunnel intersections.

There is a need to scope the importance of the mechanical properties of the brittle deformation zones from a long-term safety perspective (noting the potentially limited significance of such zones in the near-field). This could now be more worthwhile, using the estimated ranges of deformation zone properties as input. The properties are clearly important for the rock mechanics design. The mechanical properties of the brittle deformation zones may be estimated using four methods (in full cooperation with the...
geological team): i) empirical evaluation from the core data from the re-logging of the drillholes, the $Q'$ values (see Chapter 5 for an explanation of $Q'$) and the photographs; ii) by numerical modelling; iii) by indirect seismic measurements; and iv) by back analysis from observations made in the ONKALO ramp.

I9: Thermal properties

The thermal properties are important, because the location and spacing of deposition holes and tunnels are a function of the thermal conductivity and diffusivity of the rock mass.

As further discussed in Chapter 5, there is generally high confidence in the thermal data. Thermal properties are mainly measured in the laboratory on small-scale samples, but additional in situ data are obtained from the TERO probe, that also measures at the more relevant metre scale. Current results suggest quite good correlation between these larger-scale data and the upscaling of the laboratory data, thereby enhancing confidence in the upscaling. Laboratory data suggest some thermal anisotropy, but the potential thermal anisotropy at the larger scale, i.e. the deposition hole and deposition tunnel scales, is not known in detail. Scoping calculations suggest that the effect of this potential anisotropy depends on the repository orientation in relation to the foliation, and that, at least for the assessed tunnel orientation in relation to the foliation angle, it is not very important for the thermal evolution.

Tests should continue to be carried out on small samples and in situ using the ONKALO tunnel. Below HZ20, it could be useful to carry out a heater experiment (possibly combined with the spalling test discussed in I6), with detailed temperature monitoring. That would allow further assessment of how to upscale the thermal data to represent the heat conduction at the canister scale. Later, during the construction and operation phase of the repository, monitoring of the thermal properties of the rock locally will be necessary for verifying the thermal dimensioning of the repository.

10.3.3 Hydrogeochemistry and hydrogeology issues

I10: Distribution of water types and consistency with flow field

The groundwater composition is needed for the Safety Case. An explanation of the distribution of water types, consistent with the hydrogeological modelling, is essential for building confidence, not only in the hydrogeochemistry model, but also in the hydrogeology and geology models. Furthermore, this understanding is essential in order to have sufficient confidence in predicting the future evolution of the groundwater chemistry.

As further discussed in Chapter 7, most water chemistry data are from the HZs and some other connected fractures of relatively high transmissivity. Given the wealth of data and their consistency, we are confident in the distribution and relative residence times of water types in the “flowing part” of the system. New data, including water samples from poorly transmissive fractures and pore waters, also support earlier observations, though the salinities are slightly lower than in the more transmissive features. The understanding of residence times and the low fraction of fresh (i.e. very dilute) meltwater, supports the idea of a hydrogeological system at Olkiluoto with a strong resistance to external changes. However, some uncertainties remain;
The water type distribution appears to be generally governed by the flow and its variation due to past climate changes. It can be generally reproduced by the hydrogeological simulations, see Chapter 6, but in places in the drillholes some differences between the model predictions and the hydrogeological simulations remain. In these cases the calculated result tends to overestimate the penetration of meteoric water and underestimate the extent of Littorina infiltration. These differences could possibly be reduced by local and detailed scale adjustments in the modelled initial state or the model properties (i.e. flow/diffusion porosity, effective conductivity, etc.) around the drillholes assessed.

Recent data from the ONKALO indicate that the salinity in poorly-transmissive fractures at the depth of the SO$_4$-rich groundwater layer is slightly lower and the mean residence time longer than in baseline data from the field. It appears, therefore, that the infiltration of Littorina water at these depths has not reached high fractions within the poorly-permeable parts of the rock. However, the groundwater is brackish and relatively older than in the more transmissive fractures sampled from the surface. Pore water studies indicate even lower salinities and longer residence times where diffusion-dominated solute movement exists. However, there are only a few results on pore waters at the moment and more data are needed before a more definitive conclusion can be drawn.

Chemical data also suggest that HZ19 is not a simple infiltration zone, rather it is a mixing and even a discharge zone, at least close to the surface. Chemical data may even suggest that HZ19 is partly isolated, and the possibility needs to be considered as to whether there is any flow at depth within HZ19. Connection to the boundary of the model is needed for any flow to take place in HZ19.

There is less knowledge about pore water compositions, i.e. the water inside the rock matrix. A few microbial, porewater and fracture surface data now exist – but more data are needed before any definite conclusions can be drawn.

The following planned or considered actions would help resolving these uncertainties:

- More data are needed from the pores and poorly-connected fracture system. Hydrogeological and chemical investigations and experiments of poorly-transmissive fracture systems are an important step in obtaining more information on groundwaters and salinity in different hydrogeological conditions vs. depth.
- Data from the sub-sea drillhole (OL-KR47), pore water and palaeohydrogeological studies will provide further information on the heterogeneity of the distributions of groundwaters and salinities in the past and at the present.
- More data are needed from the poorly-permeable rock, also below HZ20, with continued investigations from drillholes and the ONKALO.
- Experiments carried out at different scales in the ONKALO may provide more detailed information on groundwater flow in single fractures and hydrogeological zones.
- The infiltration experiment investigating groundwater recharge to HZ19 started in 2008. The experiment will continue for a few years, and the first analyses will be available during 2009.
Hydrogeological models would need to include all relevant hydraulic features (e.g. as splays of major hydrogeological zones) in order to improve the consistency between the hydrogeological simulations and hydrogeochemistry. This would make it possible to ensure the infiltration of Littorina water into all relatively highly-transmissive features (> $10^{-7}\text{ m}^2/\text{s}$, cf. Figure 7-7) and would allow the hydraulic conductivity in the less permeable parts of the model to be reduced, thus increasing resistance against meteoric infiltration.

I11: Evolution of groundwater composition - flow paths to/from the host rock, especially the near-surface interface

Understanding the flow paths to and from the repository host rock affects the ability to predict future groundwater compositions.

As shown in Chapters 3 and 7, the understanding of the connection between the near-surface waters (i.e. surface waters and shallow groundwaters mainly in the overburden) and the waters in the bedrock has advanced due to the development of the near-surface hydrogeological modelling. However, some questions remains:

- Is there hydraulic anisotropy near the surface? The very high hydraulic anisotropy (of 60) assumed in SR2006 was basically a fitting parameter, with little direct support from any data. In SR2008 it seems that there is less need for assuming such a high anisotropy in the Littorina simulations, although a factor of 10 is still required. Given that the flow is controlled by the fracture system, it would not be unusual to expect an anisotropy to develop. The block-scale hydrogeological DFN simulations do indeed suggest some anisotropy, with higher permeability in the horizontal direction.

- With regard to the operational phase, it is noted that inflows generally decrease with time. This is usually attributed to calcite precipitation, but the understanding is incomplete. Probably the carbonate is taken from the surface and the calcium from grouts in the rock. It is the availability of carbonate that limits the formation of calcite.

The infiltration experiment, see I10, will provide relevant data on this issue. Modelling of the interface between the near-surface system and the hydrogeological system at greater depth interface will continue.

I12: Evolution of groundwater composition- Impact of surficial water intrusion (pH, Redox and buffering capacity)

Seawater (in addition to meteoric water) intruding the site or the mixing of former marine waters will affect the groundwater composition. Understanding pH, redox and the buffering capacity of the rock is essential for predicting the impact of surficial water intrusion.

The status of this issue is essentially the same as in SR2006, but Chapter 7 concludes that more data enhances the level of confidence, though only slightly. Reducing and neutral hydrogeochemical conditions are clearly buffered in the natural state, but modelling calculations suggest significant consumption of buffering minerals, if aggressive meteoric infiltration is high. Some key uncertainties remain:
Samples with elevated sulphide concentrations are found. Conceptually, the process of sulphate reduction is clear and is only possible through microbial activity at these temperatures, but the quantification of the microbial activity, particularly the rate of sulphate reduction, is uncertain.

There are also uncertainties in the flow paths (see I11). This especially concerns conditions during the construction and operational phase, when the possibility of direct connections from the sea down to the open tunnels has to be considered. The rate of migration would also depend on the porosity.

There is evidence that the presence of elevated dissolved sulphides is due to disturbances caused by investigations (e.g. open borehole flow, pumping effects etc.) and in natural conditions mixing between SO$_4^-$ and CH$_4$-rich groundwaters is limited and microbial process stabilised. The results of stable isotope analyses indicate that microbial processes have been relatively limited (not pervasive) at the site.

Dealing with this issue includes both numerical flow modelling and in situ monitoring of the chemical composition of water samples and the flow field:

- Detailed characterisation and evaluation of fracture minerals (e.g. their buffering capacity, palaeohydrogeochemistry) and pore water is important. An experiment to study meteoric infiltration has started, see I10.
- Processes activated by seawater intrusion can be evaluated, using the long-term OL-KR6 pumping test as a starting point. The analyses of chemical and microbial data, integrated with improved hydrogeological understanding around the drillhole, is continuing.
- A biogeochemical experiment in an investigation niche will be organised just below HZ20 to evaluate SO$_4^-$ reduction due to groundwater mixing. The data of C and S species in groundwater, gases, isotopic compositions and microbes, compiled during the experiment, may give further details of past processes. The kinetics of microbial SO$_4^-$ reductions have already been tested in reactive transport simulations.
- The monitoring programme will also give information on the movements of marine waters and chemical changes.
- A palaeohydrogeological evaluation of fracture minerals may give more information from the distribution of microbial sulphate reduction and seawater intrusion in the groundwater system.
- Numerical flow modelling should also be able to guide sampling from locations that are anticipated to be experiencing seawater intrusion.

**I13: Evolution of groundwater composition: Formation of gas phase/ dissolved gases in groundwater.**

Methane data suggest that there is a potential gas phase in the deepest groundwaters. Near-saturated groundwaters may form a gas phase due to upward migration (leading to decrease of ambient water pressure) and/or the warming of groundwater. Upward migrating methane may also cause sulphate reduction.
Chapter 7 and previous reports assess the current site knowledge, based on a lot of deep gas samples, and shows that the situation at Olkiluoto is not anomalous, as there are several other locations in the Fennoscandian Shield with high methane concentrations, which could be the effect of a well-buffered system with reducing conditions. There is a good understanding of the origin of the methane, and there are bacterial and thermal end-members. Bacterial methane is formed at ambient temperatures and has a lower proportion than thermal methane, which is most probably abiogenic and formed at considerably higher temperatures. However, both the current accumulation rate and source of methane production are uncertain, albeit believed to be very slow.

- At depth the methane concentration is close to the saturation limit. Secondary fluid inclusions have been observed to contain high methane contents, therefore thermal methane can also have an in situ source and has not necessarily diffused from great depths.

- The current rate and source of methane production is unclear. Is its production really common in the upper 1000 m? If it were a fast process, the whole volume should be saturated with methane – but it is not. Is it limited by the availability of source compounds, hydrogen in particular? Active methanogens are observed.

- The thermodynamic data of the gas-mixtures are poorly known.

It is essential to obtain more data (gas contents, microbes, isotopic) from deep, saline groundwaters, and drillholes, possibly deeper than the existing ones, but further away (i.e. not in the repository volume). Gas data will be integrated with isotopic data of fracture calcites and pyrites, which will provide information on methane consumption and production. New gas data are also planned to be obtained from the matrix pore space. The gas phase is an uncertainty, which probably cannot be verified with current sampling methods. Modelling may help in understanding the accumulation of methane in the system and whether oversaturation is possible. Methane diffusion can be evaluated by studying helium gas evolution, which may give more information on the methane fraction from different sources and its rate of accumulation.

**I14: Evolution of groundwater composition: Evidence of deep infiltration of dilute waters**

Dilute waters and dissolved oxygen may be detrimental to buffer stability and causes canister corrosion, respectively. As assessed in Chapter 7, the infiltration of dilute waters, such as glacial meltwater or meteoric recharge to repository depths, seems improbable, according to groundwater and pore water data, although flow simulations may suggest this possibility. Glacial components are present in mixtures of more saline and diluted waters. No signs of the existence of fresh waters at repository depths have been observed at Olkiluoto, at least not for the Quaternary period.

- Essentially, all fractures are covered by fracture minerals and there is no evidence of the recent corrosion of these minerals.

- Pore water studies do not support the penetration of any glacial water (i.e. dilute waters) into the bedrock.

The non-existence of previous diluted conditions and preserved anaerobic conditions should be further confirmed by palaeohydrogeological studies and groundwater studies.
from poorly-transmissive fractures and from pore space. Calibration with the flow model will determine the potential for the penetration of deglaciation waters to great depths. The Littorina model will also be extended and tested to include the deglaciation phase. Palaeohydrogeological studies of fracture minerals and U-series measurements in fracture interfaces will give additional data from previous deglaciations. Further action is needed in investigating the locations of the ice margins from the latest glaciations and the related deposits, where hydrogeological conditions have been stable.

**I15: Evolution of groundwater composition: Potential for upconing of very saline water**

High salinity affects the stability of the buffer/backfill. High salinities in the repository host rock block may have a great impact on the technical planning (and cost) of the final repository. Knowledge of the salinity also supports the site-specific groundwater flow modelling.

As shown in Chapter 9, all model calculations to date have indicated the potential for meeting higher than current salinities at repository depths. The degree of upconing will partly depend on the hydraulic connections to the saline water and the ONKALO. Given that it is a fracture system, the temporal evolution and exact locations of these intrusions will be very hard to predict in detail. It will be very hard to totally discard the possibility of intrusion of water with a higher salinity than the present value, despite engineering actions (e.g. grouting) to mitigate the problem.

Predicting upconing requires – besides knowledge of spatial groundwater extraction rates and evolution of the water table – site-specific information about the hydrostructures, their properties (transmissivity and flow porosities), the location of the freshwater–saltwater interface, and the salinities of deep groundwaters. Groundwater samples are taken from locations of good yield, i.e. hydrogeologically well-connected locations, which means that the samples are mixtures of less and more saline waters than the original salinity at the sample point.

Some understanding of the location of the interface has been developed: no sharp interface exists at the site scale, but there seems to a well-defined transition zone with a width of a couple of hundred metres. (Note that the literature on upconing usually concerns a more idealised situation, in which an (eventually) sharp steady-state saltwater interface is maintained below the “sink” (usually a drillhole) and the conditions that should be met so as to prevent the interface’s movement to the sink. In reality, and especially in a heterogeneous medium, such as fractured rock, a sharp and steady interface is not to be expected.)

The issue is currently handled by monitoring during construction and taking actions (grouting etc.) if there are signs of upconing. Future updates of the hydrogeological/hydrogeochemical modelling, making use of the additional site data, may enhance the predictive capability. The drillhole beneath the sea (OL-KR47) may contribute considerably to our understanding of the past evolution of the saline interface and thereby help in a more definite evaluation of its future movement. More data from deep groundwaters would be helpful, although it is known that the observed salinities are quite high at Olkiluoto. In principle, denser water (i.e. more saline water) is less prone to upconing. Numerical modelling is a good means of assessing the impact of uncertainties on the magnitude of this effect.
10.3.4 Transport properties

I16: Site evidence for flow related transport properties of migration paths from the potential repository panels.

The flow-related transport properties of the potential migration paths are needed for the Safety Case. They are assessed in Chapter 8.

Direct site evidence on the migration properties in parts of the rock containing few and poorly-transmissive fractures is hard to obtain, and the properties have to be assessed via modelling. Compared to previous migration models (e.g. in TILA99, Vieno and Nordman 1999), the current migration modelling, based on the new hydrogeological DFN, is judged more realistic, as it aims to capture the spatial variability of the flow along migration paths, the retention properties along the migration paths, and their correlation. The properties used in this model are obtained directly from the site-specific data and from the other models of the Olkiluoto site.

- Several alternatives regarding e.g. fracture size, fracture frequency and correlation between size and transmissivity, see Chapter 8, are presented and assessed.

- Characterising the flow distribution is mainly related to the description of how the potentially-transmissive fractures form a connected network. The flow cannot be measured for future conditions, the flow path distribution has to be based on modelling, i.e. the hydrogeological DFN and estimates of the future boundary conditions.

The question is then whether the hydrogeological DFN is sufficiently bounded by the available hydrogeological data. This is the same issue as already discussed in issue I4, see above.

I17 Site evidence for the retention properties of the rock from the potential repository panels

Matrix retention properties are needed for the Safety Case and are assessed in Chapter 8.

Data on retention properties are obtained from laboratory tests on core samples. A few such samples from Olkiluoto exist and have been analysed, but there is a question as to whether these samples are representative of the actual migration paths.

- There are samples from the HZs, but these contribute little to retention, even if they are important for the buffering of intruding waters.

- There are also samples from the less conductive parts of the rock mass, but coupling these to the migration paths in this rock can only be made using a statistical approach. This needs further development.

- Another issue worth consideration is whether long-term changes of the minerals on fractures and in the matrix, due to precipitation and dissolution, would imply that retention properties change over time. The great age of the fracture minerals suggests this is not an issue – but this has not been formally assessed yet.
• There may also be a bias associated with porosities measured in the laboratory, as these may possibly be affected by stress release. Only a few sorption coefficients are obtained from in situ tests. The understanding of sorption, and its dependence on groundwater chemistry, needs to be supplemented by generic data.

The current scarcity of data needs to be handled in order to enhance confidence. The following actions are needed:

• The further development of a statistical approach for judging the representativity of samples. Some information on this will come from the assessment of fracture mineralogy. Part of this assessment will be to consider whether there really are statistically different properties in different fractures or in different parts of the rock

• An assessment as to whether retention properties change over time.

• An assessment of the potential biases due to stress release, e.g. by comparing with in situ methods such as electrical resistivity logs.

• Statistical representativity of the rock matrix retention properties will be supported by the characterisation programme planned for the rock volumes below zone HZ20. The measuring programme will include characterisation of the drill cores in order to identify immobile retention zone properties, studies in the ONKALO of the in situ diffusivity studies and investigations of the sorption properties of the altered and unaltered rock matrix from core samples of the representative drillholes.

10.3.5 Overall site understanding and predictability issues

I20 Relationship between pilot hole data and conditions in the excavated tunnel and its environment

Pilot hole information is judged essential for judging whether a specific deposition tunnel is acceptable. It is thus essential to establish how well the pilot hole data are correlated with the local rock mass properties around the hole. This is also important from the perspective of an overall understanding of the site. This issue is a key part of the Prediction/Outcome studies presented in Chapter 9.

There is generally a good correlation between what has been seen in pilot holes and what is then encountered when mapping the excavated tunnel, but there are some discrepancies.

• The fracture frequencies measured on the pilot hole drill cores are currently higher than the frequencies mapped on the adjacent tunnel walls. It is still unclear whether this is due to the difference in the resolution of the mapping of the tunnel walls and the pilot hole core, or if the core contains artificial breaks. This problem raises the general question regarding the reliability of the fracture mapping of any drill core.

• Predictions of rock mass stability and the actual behaviour of the ONKALO tunnel, or measures taken for reinforcement, show some discrepancies. Pilot hole data generally show that the rock is between good and very good and this is also generally the case in the excavated tunnels. However, the pilot holes do not supply

10 There are no issues I17-I19!
sufficient information to allow the identification of isolated stability problems. The
diameter of the pilot holes is too small to reveal the exact locations of potential
unstable rock blocks, even if the pilot hole data usually are sufficient to tell what
type of rock fracturing has been intersected.

- Inflows to the ONKALO tunnel are disturbed by “skin effects” and grouting,
making quantitative comparisons between pilot hole data and actual tunnel
conditions difficult. In addition, fracture transmissivity varies within the plane of a
fracture. However, some qualitative observations can be made. Usually, the pilot
holes predict higher inflows than actually observed, but there are several occasions
where the pilot holes suggest dry conditions – but where it eventually was necessary
to grout (based on probe hole data) or post-grout due to unacceptably high inflows.
Closely spaced pilot holes, i.e. in the shaft, showed quite different hydraulic
condition. The inflow points for the high T fractures are essentially the same,
wheras the low T fracture inflow points differ. Transmissivity values differ by up
to an order of magnitude between the pilot holes.

- Water samples taken from the ONKALO appear similar to the water samples taken
from the pilot holes. Samples taken from the ONKALO also correspond well with
field data, in general. However, pilot hole samples from sections of low
transmissivity and high porosity, i.e. with hydraulic conditions which differ from
those outside the ONKALO, also deviate to a certain extent from the general trends
(cf. issue I11). Such samples are, for example, found in ONK-PH2, ONK-PH6,
ONK-PVA2.

An effort is needed to further explore the reason for the differences between the fracture
frequency in pilot hole drill cores and the mapped fracture frequency on the tunnel
walls. It may be considered sensible to remap a drill core section (e.g. discarding
mapped fractures parallel to the foliation) and remap a section of the tunnel wall at high
resolution, and then to compare the outcomes.

A numerical analysis of the correlation between transmissive sections in closely-spaced
pilot holes should be made with the hydrogeological DFN. It would also be of interest if
the number of “inflow points” in the tunnel and in the pilot holes could be compared, cf.
discussion on issue I4.

Detailed hydrogeological characterisation of, for example, a niche, would give some
further indication of the spatial heterogeneity of the flow system (see also issue I4).

I21 What is the scale of natural variability of deformation zones?

Information about deformation zones is needed for the safety case. Establishing
guidelines for the definition of the deformation zones (i.e. core and zone of influence)
would be very useful for verifying the location of the layout-determining features from
investigations carried out underground. The current level of knowledge is addressed in
Chapter 4.

The cores and influence zones, are established for the larger deformation zones (see
Chapter 4) which shows the variability of the properties of the zones in drillhole
intersections. For site-scale zones, the core sections are usually on the scale of 10 cm to
metres, whereas the zones of influence are in the order of tens of metres. Tunnel
observations also indicate that the intersected local deformation zones usually have a variability in the core thickness from few cm to few tens of cm.

Work is under way to characterise the variability of the influence zones of local deformation zones, something that is very dependent on tunnel observations. The issue is important in order to assess the uncertainties within the modelling of local deformation zones and also for the RSC program when considering avoidance criteria for such zones.

I22 Capability to predict spalling

The occurrence of spalling is of direct relevance to the Safety Case, and for the construction work. The basic data for making predictions of spalling are provided in Chapter 5, whereas Section 9.3 addresses the observed and potential spalling during the construction of the ONKALO.

Based on strength and stress estimates, it is possible to assess whether spalling is likely to occur. It seems that the few occasions of observed spalling in the ONKALO occur at the expected tunnel orientations.

- The uncertainty in stress (see issue I6) and the spatial variability of rock strength (see issue I7) result in uncertainty regarding spalling predictions.

- In relation to the potential for spalling in the deposition holes, there is uncertainty in fully understanding and quantifying the importance of a counter pressure to suppress the spalling, even if it is clear that a quite moderate counter pressures (in the order of 0.5-1 MPa or less) would be sufficient.

Uncertainty regarding the extent of spalling will be reduced by reducing uncertainty in the magnitudes of the stress and the rock strength (see issues I6 and I7), although there is a element of spatial variability that cannot be reduced by such data. Scoping calculations, which will include the thermal evolution, on the importance of counter pressures on suppressing the spalling will continue. Current SKB experiments in the Äspö HRL may also provide new insights in this area.

I23 Characterisation of the Excavation Damage Zone (EDZ) of the ONKALO tunnel system

The properties of a potential excavation damage zone is of importance for the safety case. Tunnel excavation, in particular with rock blasting, is seen as susceptible to the emergence of an EDZ. The EDZ may also alter the rock’s hydrogeological characteristics significantly. The hydrogeological characteristics may change through blasting-induced fracturing but also due to spalling if it occurs. The current knowledge regarding the EDZ is discussed in Chapter 9.

Experience to date suggests that there is likely to be a more extensive EDZ in the tunnel floor. There are still only a few hydraulic data on the EDZ and, although they suggest that the transmissivity of the EDZ is quite low, their interpretation is difficult and the results uncertain. Thus there are good reasons for trying to further characterise the EDZ. It needs also to be realised that the EDZ’s characteristics may be very different during the construction of the ONKALO, when the tunnel is open, from after the closure of the repository, when it has been backfilled and becomes resaturated. The hydrogeological
literature terms this kind of EDZ as tunnel skin, which, actually, contributes favourably
to the tunnel’s hydrogeological isolation from its surroundings during the stage of open
tunnels; but which evolves into a potentially conductive hydrogeological feature after
resaturation.

New EDZ holes and niche studies are planned in the ONKALO and plans for a
hydraulic characterisation of the EDZ are being formulated.

I25: Impact of the open drillholes on the hydraulic connections of natural
deformation zones.

As discussed in Chapter 7, the hydrogeochemical samples are affected by the presence
of open drillholes, which affects the characterisation of the groundwater composition,
needed for the Safety Case.

Multi-packers have now been installed in most drillholes that previously were open.
This issue is not seen as a major concern any more. Monitoring the recovery of these
boreholes from their open stage will continue.

I26: Existence of high pH plume and other impacts of grouting

A high pH is potentially detrimental to the buffer and the potential for such plumes is
essential information for the Safety Case.

As further discussed in the previous Site Report (Andersson et al. 2007), fracture
minerals (in addition to CO$_2$ in groundwater) are able to neutralise a high pH plume,
although the kinetics of these processes are very uncertain. To date there are few
indications of elevated pH from the groundwater sampling. At some points pH values
above 8 are found, but these values are caused by natural processes, and need not be
related to the grouting. The influence of grouting cement has also been monitored in
drillhole experiments at shallow depth in the ONKALO. The results showed a
significant decrease in pH values over a few years, but the experiments were not
hydrogeologically well controlled (Arenius et al. 2008). It should be also noted that the
ONKALO is now approaching depths where the natural pH buffering capacity is lower.

The monitoring of pH will continue. A well-controlled experiment could possibly
provide further insights into whether a pH plume really develops. Reactive transport
modelling exercises (e.g. as part of the Prediction/Outcome studies), to improve the
understanding of the ability of local water-rock systems to neutralise high pH water,
may also be worthwhile.

10.4 Data support, confidence and uncertainty in the resulting SDM input
to the safety case

Table 10-1 of Appendix 10 shows how the Olkiluoto Site Descriptive Model (SDM) is
used in the Safety Case. Table 10-2 of Appendix 10 discusses the main remaining issues
in deriving this site description. However, for reasons of traceability in the Safety Case,
it is also important to document the source of information for the SDM, the quality of
this information and the resulting uncertainty and confidence. A summary table, Table
10-3 in Appendix 10 has been assembled covering:
• For a specific SDM property, how this is used as input to the Safety Case (reference to Table 10-1 of Appendix 10)

• Characterisation data and other aspects supporting the estimate of the property (just a list with reference to the appropriate section in the main text)

• Have all available, relevant data/information been used for assessing this property?

• Is there low accuracy or pronounced bias in the information used to estimate the property? If so, what is the extent of this inaccuracy or bias and how has it been accounted for?

• Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of useable site data, etc.)?

• Are uncertainties in the property bounded, and with what confidence? Are there contradictory data that may even suggest a potential for alternative interpretation/models?

• What are the main reasons for this confidence (or lack of confidence)?

The inputs to the Safety Case are described in the following subsections.

10.4.1 Geology

The lithological model, presented in Chapter 4, is based on core logging, surface mapping, ONKALO tunnel data, petrophysical sampling and magnetic measurements, as well as on the understanding of geological history of the site, especially of the ductile deformation, which directly affects the lithological distribution.

• The relationship between block faulting and lithological distribution has not been assessed and, if the displacement of the faults has been significant, this should be reflected in the lithological model. The lack of proper key markers makes this assessment difficult, but will be nevertheless considered within future work.

• There is no bias at the site-scale, as the new drillholes seem, more or less, to confirm the results of earlier models.

• In the eastern part of the island there is a low data density, but new drillholes and other investigation techniques will resolve this issue. The uncertainties in the understanding of ductile deformation are directly linked to the lithological model.

• Uncertainties in the site-scale lithological model are considered to be bounded, as the key aspects controlling the lithological distribution are known and the data coverage is mainly good.

The confidence of the site-scale lithological model is considered as high in the well-investigated area, as shown by prediction-outcome work. Due to a poorer data density, the confidence in the eastern area is lower.
The **ductile deformation model** is based on core logging, surface mapping, ONKALO tunnel data, magnetic measurements and on the understanding of the ductile deformation history.

- Data on the foliation at the small-scale have not yet been made use of as fully as might be, and the relationship between block faulting and the ductile deformation model has not yet been fully assessed, e.g. ductile kinematics, ageing methods, and plate tectonics studies can probably be used more efficiently by suitable sampling of the features of different deformation phases.

- There is no bias at the site-scale, as new drillholes seem, more or less, to confirm the results of earlier models. However, the ductile deformation model is continuously developed as new data are acquired and, as a consequence, the precision of the model is also continuously increasing.

- There is good data coverage in the site-scale model, but for the modelling of small-scale variation of, for example, folding and foliation, the site-scale coverage may not be sufficiently high.

- Uncertainties in the site-scale ductile deformation model are considered to be bounded, as the site-scale understanding of the ductile deformation seems to be quite robust with respect to newly-acquired data. For small-scale variations, the uncertainties are not that well-bounded and further work is needed to assess the effect of such variations. This assessment should of course be linked to the needs of the end users of the data, i.e. what is the required resolution?

There is high level of confidence in the model, since it seems to explain the current observations.

The **spatial alteration model** is based on core logging, surface mapping, ONKALO tunnel data, gamma measurements and the understanding of the alteration processes.

- The relationship between fracturing, faulting and alteration has been assessed in the current models, but this assessment should be further continued in order to increase the understanding of the alteration processes. The physico-chemical properties of the altered rock types are still under investigations and these data should be taken into account, when available.

- There is no bias in the data and they are considered precise.

- The low spatial coverage in the eastern area affects the confidence in the model in the eastern part of the island.

- Currently, the alteration model only accounts for the spatial distribution of pervasive alteration, whereas fracture-controlled alteration is also common.

- The current understanding of the spatial distribution of the pervasive alteration is considered to be fairly good, yet the degree and properties of the alteration, which are currently under investigation, may result in additional uncertainties to the current model. The currently-modelled volumes of pervasive alteration may contain more heterogeneous smaller volumes with respect to their physico-chemical properties.
Once data on this factor have been obtained, their effect on the current model needs to be assessed.

The level of confidence in the model is judged to be high, since the new data obtained to date have more or less confirmed the results of the model. However, the issues stated above need to be taken into account in future modelling work.

The deformation zone model is based on core logging, surface mapping, ONKALO tunnel data, magnetic measurements, mise-à-la-masse measurements, VSP, 3D seismics and the understanding of the brittle deformation history. Modelled deformation zones outside the well characterised area are only based on seismic data and the understanding of the brittle deformation zone history.

- The 3D seismic data can be further explored to obtain an understanding of the age relationship of various faults, and the relationship of modelled local-scale faults and site-scale faults should be further assessed.

- The current drillhole geometry potentially limits the possibility of intersecting subvertical faults, yet the data density in the central part of the island is high enough to reveal any site-scale subvertical faults, and this bias is therefore related to local-scale faults.

- The extrapolation of site-scale faults outside the central part of the island is a source of uncertainty. The extrapolation is based on some geophysical data but also on expert judgment – direct control is lacking on these areas.

- The exact nature of the bounding lineaments is currently unknown, due to a lack of data. The small number of drillholes increases uncertainties in the eastern part of the island.

- The main uncertainties in the deformation zone model are known and work is currently taking place to limit the importance of the remaining uncertainties. New uncertainties are not expected.

There is considerable confidence in the geometry and extent of the site-scale faults within the central part of the island, as demonstrated by the new data. The level of confidence regarding the extent and geometry of the site-scale faults in the eastern part of the island is lower.

The fracture description and the geological DFN model are based on core logging, mapping of trenches and ONKALO mapping.

- There is a good understanding of the fracture filling mineralogy, but no correlation with other fracture attributes. Further studies are needed to clarify the properties of typical fractures in the bedrock by combining, for example, their geometry, mineralogy and porosity profiles.

- The DFN modelling is based on the mapped fractures in the drillholes and in the first tunnel sections of the rock volume. This and the potential for greater levels of near-surface fracturing can cause biases in fracturing models. This bias will be corrected when mapped tunnel data from greater depths become available.
• There is uncertainty in the DFN modelling, indicated by having different alternative DFN models, based on different weightings of the data. These models predict slightly different fracture patterns.

Nevertheless, there is a reasonable level of confidence in the geological DFN model, since the fracture data collected from the tunnel and drillholes and from the surface mapping show general similarities.

10.4.2 Rock mechanics

In addition to the stress data which existed before 2006, the stress model is based on shaft measurements, made in 2007 – 2008, OC measurements made in the ONKALO and a semi-integrated stress analysis.

• All the stress data have been considered but data which are judged of poor quality have not been used in specifying the stress state.

• Some test results have a poor level of accuracy, but the stress estimates have been made using the more reliable data. All overcoring data from the ONKALO suffer from irregular consistency, most probably related to the heterogeneity of the rock with respect to the test size and the behaviour of the glue used in the instrumentation.

• There is low spatial coverage (no data yet from the eastern area) and there could be areas at the site where the stress field is different because of the influence of brittle deformation zones in deflecting the stresses.

• The uncertainties are not well bounded and the range is large (cf. highest/lowest values – but need better estimates). Recent, larger-scale measurements in shafts indicate that the major principal stress may be N-S, rather than NW-SE, at least above HZ20. The magnitudes of the stresses are also on the upper bound of the SR2006 estimate.

There is an overall confidence in the stress model, because of its consistency with the regional stress state in Fennoscandia, but there is less confidence in its details, because of the potential for local deviations in the magnitudes and orientations of the principal stresses. The effect of the BDZs has not yet been studied, and such a study has been postponed to SR2010 because of small number of reliable stress data for comparison.

Intact rock properties are determined from laboratory tests on rock core samples, point load and Schmidt hammer tests on site:

• Correlation between different strength estimation methods will be done in early 2009, also checking for possible correlation with geological and geophysical mapping data.

• The data are unbiased, but somewhat imprecise, because there is a large standard deviation due to the heterogeneity of the rock. However, this is typical and accounted for by using the full distribution of rock strengths in the analyses, e.g. in spalling analyses. The effects of rock types, foliation and heterogeneity are a potential source of uncertainty, but this is accounted for by using the complete distribution of rock strengths. There is a need to clarify what this imprecision relates
to: the method of testing or the location of the samples. Furthermore, the long-term strength and spalling strength data are not yet fully understood.

- The uncertainties in rock modulus and strength are bounded.

Confidence is achieved by using the full distributions of the various parameters. The possible use of geological and geophysical mapping information has not yet been fully investigated.

Fracture properties and potentially unstable rock blocks are based on the Q mapping data. Laboratory tests exist only for one of three major types of fractures, but this will be completed in 2008/2009.

- All data are considered.

- There is no bias in the fracture property data, but they are somewhat imprecise due to the heterogeneity of the fracture surfaces. There is no bias in fracture orientations, but possibly a bias in fracture frequencies as measured in the different mapping situations; however, this bias is understood and can be accounted for.

- Uncertainties are bounded.

There is a very high confidence in the fracture geometry for rock mechanics purposes, because of the wealth of mapping data on fractures. There is less confidence in the mechanical properties of fractures.

Deformation zone properties are based on the Q mapping data where there are drillhole or tunnel intersections.

- Data are somewhat imprecise due to the heterogeneity of the fracture zones.

- There is low spatial coverage.

- A very coarse bound of the uncertainty for strength is between zero and the intact rock strength.

Confidence in the values given is limited, since no relevant direct measurements have yet been made.

Rock mass properties are assessed from the intact rock and fracture properties (see above)

- Information on in situ strength (at the tunnel scale) has not yet been studied and the currently used estimates are based on information for homogeneous rock types (at the URL in Canada, and at the Åspö HRL in Sweden). Tests on ONKALO rock types are being planned.

- There are many estimates possible, based on the Q values from drillhole, pilot hole, and tunnel mapping work. There is some incompatibility in the different Q values thus determined, but the estimates can be sufficiently well bounded. There may also be some incompatibility between the empirical estimates and the ‘theoretical’
estimates based on numerical modelling, but the latter have not yet been fully evaluated.

- Long-term strengths and spalling strengths are not yet fully understood.

Confidence is based on the ability to make sufficient empirical estimates, based on the large amount of mapping data available from the drillholes, pilot holes and tunnel mapping.

10.4.3 Thermal

*Thermal properties* are based on laboratory measurements from drillcores and some preliminary in situ measurements with the TERO probe, as further discussed in Chapter 5.

- All data are used.
- The data have no bias and have high precision, but show a large variation, which is due to the heterogeneity of the rocks at Olkiluoto.
- The spatial coverage is low. The effect of rock types, foliation, heterogeneity and upscaling is a potential source of uncertainty.
- The uncertainty is bounded. The lower end and the anisotropy of the thermal conductivity distribution are well bounded. More tests are needed to define thermal expansion properties.

Confidence is high, since there are several data, which are well supported by the geological descriptions, where the anisotropy is related to the occurrence of mica, whereas the spatial variability is essentially at a very local scale and averages out at larger scales. The TERO probe data suggest that the upscaling does not overestimate the thermal conductivity. However, very few in situ data exist today to understand the thermal properties at larger scales (i.e. the deposition hole scale).

*In situ temperature* is based on temperature logging in drillholes. All data are used and considered to be unbiased and of high precision, resulting in a high level of confidence.

10.4.4 Hydrogeology

As described in Chapter 6, the model properties of the *Hydrogeological Zones* are based on the geological BFZ model (including the model for lineaments), PFL observations for high transmissivities, responses to field activities, such as boring new drillholes, pumping tests and recoded episodes of high ONKALO inflow water rates.

- All data are used.
- Data are considered precise and unbiased, at least in the central part of the island. "Precision" is intimately connected to the scale of the model (and this basically is determined by knowledge from the drillholes). Whilst some bias may be associated with the drillhole observations, as the dominant orientation of the drillholes is close to the vertical, the supporting (geological) information implies a gently-dipping, if
not sub-horizontal, dominant fabric within the bedrock, making it amenable to investigations with high angle drillholes.

- Outside the central part of the island, the description of the hydrogeological zones is clearly more inaccurate, but this has limited impact on the flow in the central part of the island.

- Uncertainties are related to the continuation of some of the hydrogeological zones beyond the central part of the island. Also some alternative interpretations are described in Chapter 6.

There is a very high confidence in the location and average hydraulic properties of the hydrogeological zones in the central part of the island. The existence and description of HZ19 and HZ20 is consistent with all hydraulic data and is also consistent with the geological model. There is less confidence in the location and properties of the potential vertical hydrogeological zones, but the fact that very few such zones are found suggests there are very few. It may be different in the eastern area – there more data are needed before any conclusions can be drawn.

The hydraulic properties of the rock volumes between the hydrogeological zones, as described in the hydrogeological DFN model and including the division into different depth zones, are based on the geological DFN and PFL measurements, and the division into fracture domains above and below HZ20.

- Pilot hole and ONKALO data could be used more for calibration and testing of the hydrogeological DFN in future.

- There are many representative data from the central part of the island, but few from the eastern area. Also, the intensity of PFL data is low below approximately 400 m depth, thereby increasing the uncertainty.

- The uncertainty in the hydrogeological DFN concerning fracture size and frequency is handled using different alternatives. It is judged that the range of these alternatives bounds the uncertainty.

The hydrogeological DFN, with its alternatives, reflects the measured PFL data. This means that there is high level of confidence in the central part of the island, but less confidence outside this volume. There is less confidence with regard to fractures with transmissivities less than the PFL measurement threshold, since the model then depends on assumptions on the fracture size distribution and the transmissivity distribution of these low transmissivity fractures.

The equivalent porous medium (EPM) model at the site scale is based on a great body of hydrogeological data (PFL/HTU transmissivities, responses to various field activities, pumping tests); it is also reconciled with the geological brittle deformation zone model.

- All data are used.

- Some bias may arise from the fact that rather few actual observations are available from the uppermost 50 m of the bedrock, as most of the deep drillholes have been equipped with surface casing.
Uncertainties are similar to those in the Hydrogeological Zone (HZ) model: outside the central part of the island the undetected, and thus unknown, local structures are taken into account in the hydraulic conductivity of the sparsely-fractured rock. The uncertainties are bounded to some extent with sensitivity and uncertainty analyses.

All the data are in agreement with the model, as it has been developed to explain the existing data.

The confidence in the model stems from the huge amount of data on which the model is based.

The present day boundary conditions for water pressure and salinity are based, respectively, on water elevations in a large number of standpipes and on seawater salinity on the top surface of the model. The boundary conditions on the other boundaries (lateral and bottom) have been assumed without any direct observational data.

All data are used.

For the present day situation, the uncertainties of the boundary conditions on the top of the model are generally small. In places, however, the uncertainty may be noticeable; especially in cases where a highly transmissive zone runs through an area of elevated terrain. One such a zone is HZ004. Moreover, whilst the uncertainties in the present day boundary conditions (water table, seawater salinity) are usually small, they are greater for the periods in the past, due to the general lack of direct information, e.g. on past shorelines.

The salinity of the Littorina Sea has been inferred indirectly. Similar uncertainties are associated with the initial state of the salinity field, whereas the uncertainty in the initial state of the water pressure for the submerged island at 8000 years ago is considered to be small.

On the top of the model the pressure boundary conditions (the water table) is bounded by the topography; the boundary condition for the salinity is bounded by the seawater salinity and the fresh water (i.e. zero) salinity.

The presence of the sea makes the general boundary conditions well known and well defined. On land there is quite a large amount of hydraulic head data, resulting in a well-defined water table. With regard to the initial state, the greatest uncertainties are associated with the salinity field. At depth the salinity distribution is well known – and bounding estimates could be made – though, at shallow depths, this is more difficult, due to the strong spatial variability of permeability (see also issue I15).

10.4.5 Hydrogeochemistry

The description of the current groundwater composition is based on groundwater samples with gas data, matrix pore water data, isotopic data and fracture EC data, as described in Chapter 7.

All data are used.
- Low permeable fractures are poorly characterised, but the number of data is increasing as a result of the ONKALO investigations and the pore water studies. Substantial differences exist between the pore water and the water sampled from fractures, regardless of the transmissivity of the sampled fractures; an effect which may be partly due to measurement bias.

- The near-field groundwater compositions will depend on the hydrogeological conditions and the disturbance caused by the repository. The original conditions within HZ20A are uncertain, due to the influence of open drillholes and, therefore, it is difficult to estimate its real hydrogeochemical significance. However, salinity simulations with flow modelling do not indicate any outstandingly fast infiltration paths.

- The groundwater composition varies slightly according to the hydrogeological properties of the host rock (low permeable vs. highly transmissive, older vs. younger), but this is controlled by the observed range of groundwater compositions and types.

- The lower salinities seen in pore water data suggest a different evolution of the salinity compared to the groundwater samples or salinity simulations. The issue will be discussed in SR2010, after more data from low transmissivity fractures and matrix pore waters have been obtained.

- The current level of the hydrogeological model (i.e. the uncertainties regarding its details) does not provide the necessary level of detail for assessing the hydrogeochemical conditions in detail.

Nevertheless, there is reasonable confidence in the distribution of water types and increasing levels of data have not revealed any significant surprises. However, matrix pore water data from rocks at depth generally show more dilute water than in the permeable system; and the pore waters also appear to be very old. The origin of these dilute waters is uncertain, but their presence suggests a very low rate of exchange between the deep and near-surface groundwaters.

The assessment of chemical processes is based on groundwater samples, isotopic data, microbial data, dissolved gas data, fracture mineral mapping, analyses of mineral compositions, palaeohydrogeological studies of fracture mineralogy, isotopic studies of fracture minerals, fluid inclusions, information from other sites (analogy studies) and thermodynamic constraints.

- The use of distributional fracture mineral analyses (based on chemical and isotopic data) to describe hydrogeochemical processes may give more detailed information at the local scale.

- Potentially poor representativity may imply some bias and different data describe different volume scales of the bedrock. Mineralogical studies have been sporadic and potentially important information may have been lost due to the resulting limited volumetric representativity. Different data may represent different time episodes, thus integrated interpretations may be misleading, particularly when older episodes (i.e. preglacial) are evaluated. Detailed mineralogical studies of the latest fracture precipitates and pore water studies, together with sampling from low
transmissive features, may produce a more coherent picture of ancient episodes, including also variations in groundwater composition.

- Ancient episodes are not fully represented in the different databases (groundwater, fracture minerals, alteration).

There is a fair level of confidence in recent processes since the Weichselian glaciation. Confidence is enhanced by the general understanding of hydrogeochemical processes, geochemical reactions are universal, and by the evidence that the palaeohydrogeological evolution is well understood. The sequence of older episodes is undefined and such episodes may also include unidentified processes.

10.4.6 Transport properties

The transport model uses the hydrogeological DFN model, as described in Chapter 6, as the main input for deriving flow-related retention properties.

- Flow logging of the shaft boreholes has not yet been used for the hydrogeological DFN and subsequent transport modelling. These data could be used to assess the heterogeneity of the fracture planes and such an analysis is planned for the next update of the model.

- The hydraulic properties of the hydrogeological DFN model at the lower end of the range of fracture transmissivities could be affected by the detection limit of the PFL device, especially if fracture transmissivities well below the PFL detection limit are included in the model. Also, the connectivity of the hydrogeological DFN model depends on the ratio of open (potentially water-conducting) to flowing fractures, although there is no clear indicator for the presence of open fractures.

- The present hydrogeological DFN model is based on drillhole data from the central part of the island. This means that fracture statistics from the eastern area are not well sampled.

- An estimate for of the lower bound of the “transport resistance” (WL/Q) over all fractures and the whole island is feasible, as there are correlations between flow-related retention properties and other hydraulic properties. The bounds of the WL/Q can be estimated when flow paths are conditioned to, for example, certain flow rates.

- Uncertainties related to the structure of the hydrogeological DFN model are handled by alternative models.

The nature of the transport resistance is so close to what is actually measured by the PFL, that confidence that the models can be calibrated to the relevant data is high. Nevertheless, there are still uncertainties in the hydrogeological DFN model, but these can be bounded using alternative models (see above). Although total confidence in the precise predictions of the models is lacking, there is confidence that the uncertainty in the models and the model results can be sufficiently well bounded.

The input to the matrix properties are the geological conceptualisation and definition of the immobile zone, see Chapter 8, which in turn are based on core samples taken from OL-KR12 for the porosity and diffusion studies, and from OL-KR38 and OL-KR39 for
the investigation of porosity and pore structure by PMMA method. No sorption data are assessed in this report.

- More use could possibly be made of the geological data in determining matrix migration properties. It is possible that the properties of all the immobile zones of the retention models cannot be directly measured; and they need to be based on concepts, such as the dependence of the diffusivity on the porosity (Archie’s Law). Sorption properties for some of the immobile zones need to be estimated based, for example, on cation exchange capacity.

- The conceptual retention models are inherently quite uncertain, because of the significant heterogeneity of and variability between hydraulic features. An in situ measurement programme will be initiated in order to collect appropriate migration data.

- There is uncertainty as to whether laboratory data are biased compared to in situ data. The means of bounding this uncertainty are being explored (see issue I17).

- Inevitably matrix data will be measured at a few scattered locations in the ONKALO. However, data can be compared with relevant information from other sites, for example SKB data.

- Cogent arguments can be presented for defining the lower bounds for matrix diffusivity.

The fact that only limited matrix data are available reduces confidence in the matrix-related retention properties. In general, matrix data from different sites, e.g. the SKB sites, tend to show rather similar values of formation factors and sorption properties. This could suggest that the fact that there are few matrix data from Olkiluoto is of less concern, at least for justifying the lower bound values. Current models simplify the spatial variability and limit the differences between fractures. There are still too few site-specific data on the matrix properties.

### 10.4.7 Conclusions

The following general observations could be made:

- The site descriptive model usually depends on a multitude of data, and also uses the outputs from several disciplines to arrive at the final description. The site model properties seldom depend only on direct specific measurements.

- Generally, all data available and identified in Chapter 2 have, with a few exceptions, been considered in the modelling. The impact of not using these data is judged moderate to small.

- Poor precision or measurement biases in the field data are, with some important exceptions identified above, judged to be a minor source of uncertainty in the resulting model description.

- Low spatial coverage or lack of useable site data is an important reason for the uncertainty in the eastern part of the model domain, as well as for the uncertainty in the stress model.
Most uncertainties are bounded or handled by alternative interpretations. The main exception to this concerns the eastern area, where it is judged less meaningful to quantify uncertainties or to formulate alternatives to the stress model and the matrix migration properties, before more data are available. These uncertainties are expected to be sufficiently well bounded by the data anticipated from the planned data acquisition programmes over the coming years.

10.5 Potential for alternative interpretations

In general, few alternative models are presented in SR2008. Areas with high uncertainty, especially in the eastern area still exists, but it is usually judged more meaningful to await more data, or to provide broad uncertainty bounds for the models, rather than to develop alternative models. Alternative models are formulated where there is judged to be a limited prospect of obtaining data that would resolve the uncertainty.

As discussed in Chapter 4, there is no alternative geological model presented. The confidence in the central part of the island is now quite high. There is a need to update the model for the eastern area, once there are the necessary data. The deformation zone model in the eastern area is still unclear, since the faulting system appears to be different in some respects compared to the well-characterised area. There appear, for example, to be more vertical features in the east. Currently the DFN model, which is based on data from the well-characterised area, is just extrapolated to the east, but it is clear that the DFN model needs to be updated with data from the east, especially since the fracturing may be different there. It is judged more meaningful to wait for new data, than to formulate prematurely different alternative model to handle the uncertainty to the east.

There are three alternatives in the geological DFN model, depending on which input data are given the highest weight, see Chapter 4. The geological DFN model considers whether a fracture occurrence is correlated or clustered, but suggests that there is little evidence for this – apart from the need to divide the volume into two domains (A and B).

As discussed in Chapter 5, there is no alternative rock mechanics model, but it is noted that there are only limited data from the eastern area. Also in the central part of the island the stress orientation and magnitude are uncertain: the uncertainty being expressed by having wide bounds. Within the precision of the stress data it is possible that the orientation of the major principal stress changes with depth. A more detailed stress model will result following the evaluation of reliable stress data measured from the ONKALO below HZ20.

As further discussed in Chapter 6, there are no main alternatives to the hydrostructure model in the central part of the island, since there is considerable confidence in the model in this area. However, there are alternative interpretations for some detailed structures, see Chapter 6. There is more uncertainty outside the central part of the island. Whilst not true alternatives, there is a need to update the model once there are the necessary data. It may also be noted that the Åspö Task Force is modelling various pumping tests performed at Olkiluoto and applies different interpretations of the site hydrogeology. The findings of these studies were not available at the time of the completion of this report.
Both equivalent porous medium (EPM) and discrete fracture network (DFN) models have been derived. These are conceptually different descriptions of the **hydraulic properties**, but are judged to be consistent, i.e. their apparent differences are more a matter of scale and resolution. However, the uncertainty in the hydrogeological DFN model concerning **fracture size and frequency** is handled using different alternatives.

As further discussed in Chapter 7, there is no alternative hydrogeochemical model, but there is uncertainty in the importance and/or strength of the different hydrogeochemical processes operating. However, uncertainties have decreased due to large number of isotope data, which have clarified the processes operating at shallow depths during infiltration. Some, not yet fully explored hypotheses, concern the origin and past distribution of the saline groundwater. The diluting water component in saline groundwaters could be the result of several ice ages and periods of warm climate. The infiltration of dilute meteoric groundwater may also have taken place to greater depth than that suggested from the distribution of current groundwaters. The overall process regarding the reduction of sulphide is understood, although the rate, kinetics and constraints on the process are less well known.

As further discussed in Chapter 8, the uncertainty in the **hydrogeological DFN model** connectivity is handled by different alternatives regarding fracture size and frequency, and by different alternatives regarding the correlation between transmissivity and fracture size. There is uncertainty in the internal correlation structure between fractures, that would affect the connectivity of the fracture network. However, the hydrogeological DFN model is calibrated against the PFL data (that actually measures connectivity) and it is judged that remaining uncertainties are covered by the different presented alternatives. It is known that fractures are internally heterogeneous and sensitivity analyses are used to bound the importance of this effect. There is still an issue as to how to derive the effective properties of the network. The influence of the heterogeneity on flow has been studied using flow logging data from the shaft drillholes. In parallel with this, flow-related retention properties under PA flow conditions in heterogeneous fractures are explored using modelling studies. These studies aim to develop a methodology for relating the effective flow and the description of the retention properties in a consistent manner for heterogeneous fractures.

### 10.6 Consistency between disciplines

Another prerequisite for developing confidence is consistency (i.e. minimal conflicts) between the different discipline models. A protocol has been developed, using an interdisciplinary interaction matrix for documentation purposes, which is shown in Table 10-4. For each interaction, the following questions have been addressed.

- Which aspects of the “source” discipline would it be valuable to consider in developing the “target” discipline?
- Which aspects of the “source” discipline have actually been used when developing the “target” discipline?
- Are there any discrepancies between answers to the first and second question, and if so why?
Discrepancies between what it would be valuable to consider and what actually is considered affects confidence in the model. Again, it is primarily for the users to determine whether these discrepancies are significant or acceptable; however, an overview of this issue is provided at the conclusion of this section. In addressing the questions, effort is spent primarily on issues judged to be important and not in explaining why unimportant interactions are indeed as they appear.

Table 10-4 in Appendix 10 demonstrates the integrated character of the Site Descriptive Modelling. Different disciplines depend on the outcome of other disciplines and provide important feedbacks to those disciplines. Furthermore, to a large extent the interactions judged to be important are also considered in the modelling, and the current discrepancies between the required interactions and the interactions considered are not assessed to be a major problem in terms of the level of confidence in Site Model 2008.

Specifically, considerable attention has been paid to reaching an integrated understanding between geology and rock mechanics, see Chapter 5, between hydrogeology and geology, see Chapter 6, and between hydrogeology and hydrogeochemistry, see Chapter 7. Nevertheless, some further improvements are identified as being useful:

- The stress model could provide feedback on the character of the deformation zones. Geological domains should be harmonious with rock mechanics domains, which is especially important for P/O studies. However, such feedback was not available when developing the geological model, since it would require 3D stress modelling or new stress data.

- Stress release in cores could bias laboratory tests on matrix retention properties (formation factor). This effect has been realised but has not yet been formally analysed. The risk may also increase below the -300 m level, where the stress increases.

- Precipitation/dissolution in fractures alters their mechanical properties. This could possibly be a factor over the long-term when considering the structural integrity of the repository, but is currently not taken into account.

- The presence of a gas phase affects the flow. This is one reason for the skin needed in the inflow modelling. Detailed modelling of this is not considered in SR2008. The gas phase will, however, not remain after saturation is achieved.

- The migration properties derived should be consistent with the migration properties used in large-scale simulations of groundwater flow and evolution (cf. the Littorina studies). This has not been checked in SR2008, but should be considered in SR2010.

Compared to the development needs suggested in SR2006, there are several improvements:

- A geological DFN model has been developed and used for developing a hydrogeological DFN model for upscaling the drillhole hydraulic data.

- Feedback from the hydrogeological zones is considered when updating the geological model.
It should also be noted, that whilst a change in stress can alter the transmissivities of fractures, and that there is reason to believe that a relationship exists between the stress orientation and the potential anisotropy of the hydraulic properties, there is probably no need to consider this coupling in a more direct manner for the Site Description. The hydrogeological model developed in SR2008 is based on the observed data and there is no need to incorporate less precise relations between stress and hydraulic properties in the model.

10.7 Advances since Site Model 2006

The most important changes between SR2008 and SR2006 are:

- An expansion of the modelled area to the east.

- The geological model has been revised according to new data and interpretations. The lineament interpretation was revised and the results applied in the modelling work – the revision was based to a considerable extent on magnetic data, which seems to be the best indicator of the geometry of the brittle deformation zones. New 3D seismic data were incorporated within the model and an initial model of the eastern part of the island is provided. Site-scale brittle deformation zones are extrapolated to surrounding regional lineaments, if not prohibited by direct observations. The alteration model is revised, showing clear correspondence of illitisation with site-scale fault zones.

- A first account of the development of the brittle deformation history of the site is provided.

- The development of a new geological DFN model.

- A new stress state model and fracture and fracture zone properties are now presented. More rock mechanics data (e.g. rock response data) from the ONKALO are available.

- The development of a hydrogeological DFN model.

- An updated site-scale (EPM) flow model has been developed.

- There has been an improvement in the understanding of groundwater composition under low transmissive conditions. The importance of organics on groundwater compositions in recently-infiltrated groundwaters has been clarified, due to the availability of many more isotopic and microbial data.

- The inclusion of transport properties in the Site Report.

In other aspects of the site report, the 2008 model version is more a refinement of the 2006 model. Generally, there have been few surprises in the data obtained from the ONKALO and the Olkiluoto characterisation programmes and the revisions to the model are concerned with details.
10.8 Overall confidence

Eventually, the SDM will be used to support the safety case, and it is thus essential to establish the level of confidence in the SDM, based on the available data. Subsequent analyses within engineering and long-term safety assessment will then address whether this confidence is sufficient to warrant the programme continuing to its phase of repository construction. For this reason a new set of questions are addressed within each discipline:

- What aspects of the model (properties, specific volumes) are associated with the highest levels of confidence?
- What aspects have the lowest levels of confidence?
- What are the main reasons for confidence in the model: e.g. wealth of data, consistency with other disciplines, consistency with past evolution, stability over time (i.e. few surprises as new data arrive), other.

These questions are addressed in the following subsections.

10.8.1 Geology

The following aspects of the geological model are associated with the highest confidence:

- The geometry of site-scale structures.
- The large lithological units, and general trend of foliation in the well-known area of the central part of the island.

This confidence is due to the density and number of data used in the modelling and the understanding of the geological history.

The following aspects have the lowest level of confidence:

- The continuation of the zones outside the well-known area in the central part of the island
- The spatial distribution of small-scale features affected by different alteration processes.

10.8.2 Rock mechanics

The following aspects of the rock mechanics model are associated with the highest confidence:

- The intact rock properties.

This confidence is due to the large and consistent number of data and tests now available from the ONKALO.

The following aspects have the lowest confidence:
The stress state,
Fracture mechanical properties and
Brittle deformation zone mechanical properties

10.8.3 Hydrogeology

The following aspects of the hydrogeological model are associated with the highest levels of confidence:

- The effective properties, transmissivities and hydraulic conductivities respectively, of the hydrogeological zones and the sparsely-fractured rock in the EPM model.
- Fracture sets, orientations and flow properties for fractures well above the PFL measurement threshold in the hydrogeological DFN model.

The confidence is due to the large number of fracture data for the central part of the island and the fractures above the PFL measurement limit. The EPM model is in good agreement with the geological model. The calculated pressures in drillholes are in good agreement with observations and the calculated salinities also show a fair agreement.

The following aspects have the lowest level of confidence:

- The description of the saline water storage in matrix blocks of the EPM model.
- The connectivity and the description of the flow paths that are below or close to the PFL measurement threshold in the hydrogeological DFN model.

10.8.4 Hydrogeochemistry

The following aspects of the hydrogeochemical model are associated with the highest level of confidence:

- The general distribution of water types and gases
- The range of salinity
- The origin of groundwaters
- The main hydrogeochemical reactions and their distribution with depth.

This confidence is due to the large database and due to observations of coherent data with depth for comparable hydrogeological conditions. New data support the previous concept reported in SR2006.

The following aspects have the lowest level of confidence:

- The distribution of groundwater composition and long-term evolution of saline groundwater at the detailed scale
- The rate of hydrogeochemical reactions and the accumulation of gases.
The baseline hydrogeochemical conditions in HZ20A.

The origin of matrix pore water and its relation to groundwaters.

10.8.5 Transport

The following aspects of the transport model are associated with the highest level of confidence:

- The geometry of the site-scale flow paths is well defined by the topography and the HZs.
- The distribution of the flow-related retention properties is well bounded by the PFL data.

This high level of confidence originates from the well-established geometry of the hydrogeological zones (see Section 10.8.3) and the extensive database of PFL data that directly measures the connected transmissivity of the flow paths in the rock mass, including those outside the hydrogeological zones.

The aspects with the lowest level of confidence are:

- The heterogeneity of the transport properties in the fracture planes, where there are few data.
- The migration properties of the rock matrix (“the immobile zones”) since there are few site-specific data on these.

However, the importance of the fracture heterogeneity could be bounded by numerical simulations. The lack of site-specific data from Olkiluoto could be handled by using matrix data from similar sites, e.g. in Sweden and Finland.

10.9 General statement of confidence

There is a high level of confidence in key aspects of the Olkiluoto SDM. The main reason for this confidence is the relative wealth of data from the central part of the island and the consistency between independent data from different disciplines. There is, however, less confidence in some aspects of the SDM. This lack of confidence is handled by providing wide uncertainty ranges and bounding estimates, or by the development of alternative models. Most, but not all, of the low confidence aspects are judged to be of relatively limited importance for long-term safety, considering the data needs listed in Table 10-1 in Appendix 10. Nevertheless, the final assessment of their importance will be made within the subsequent repository engineering and safety assessment activities, and the judgement presented here is only indicative in nature. The key remaining issues concern:

- Characterising the eastern part of the island, such that the level of understanding will be comparable with that of the central part
- Further advancing the rock stress and rock strength regime for stability estimations at relevant repository depths.
• Further advancing the hydrogeochemical understanding of processes of importance for long-term safety, e.g. processes affecting sulphide content, origin of methane and redox.

• Further advancing the understanding of detailed-scale migration properties, including site-specific data on matrix properties.
11 INTEGRATED SITE DESCRIPTION

This chapter presents an integrated description of the understanding of the Olkiluoto site, based on the characterisation and observations carried out up to the end of 2007. The description and understanding are founded on a substantial amount of site-specific data, especially from the area in the central part of the Island, complemented with limited data from its eastern part.

11.1 Site Model Synopsis

11.1.1 Surface system

Formally, the surface conditions are not within the remit of the OMTF, which is concentrating on modelling the bedrock around the ONKALO and the future repository. The influence of the surface conditions on the overall system and on the conditions at depth is recognised, however, and thus a summary of climate, ecosystems and overburden properties, together with the Olkiluoto surface hydrology model is also included in Chapter 3.

Olkiluoto is a relatively flat island with an average height of 5 m above sea level (m asl), with the highest point at 18 m. The sea area around the island is shallow: mainly less than 12 m within 2 km from the shoreline. The elevations relative to sea level are continuously changing, since the apparent uplift rate is significant at 6 mm/y, mainly due to the isostatic adjustment of the bedrock to the removal of the ice load.

Currently Olkiluoto has a continental climate, with some local marine influence due to its location on the eastern coast of the Bothnian Sea, which is in the northern part of the Baltic Sea. Olkiluoto is covered by forest and shoreline vegetation, which is typical of such an island in southwestern Finland.

The overburden at Olkiluoto is mainly sandy till, and contains some clay, silt, sandy and gravel layers. In some isolated depressions fine-grained glacilacustrine sediments are also observed. The thickness of the overburden is usually 2-5 m, however in some places thicker soil layers (up to 14 m thick) have been found. The depressions in the bedrock surface are filled with thicker layers of till and the highest elevations in the bedrock emerge through the modest soil layers. In general, the sea floor deposits present a very fragmentary pattern around Olkiluoto Island - most of the sea floor being exposed bedrock or bedrock covered solely by till.

The first version of the Olkiluoto surface hydrology model was developed during 2007 (Karvonen 2008). Recharge computations carried out with the surface hydrology model revealed that the Olkiluoto bedrock groundwater system is transport-limited and the overburden supply-limited, a situation that considerably reduces the uncertainty in estimating the recharge to the sea through the bedrock system. A transport-limited system implies that there is more supply from the overburden to the bedrock than the bedrock system can transmit, which is due to the low hydraulic conductivity of the bedrock compared with that of the overburden soils. The overburden groundwater system is supply-limited, which implies that more precipitation would result in greater runoff and evapotranspiration.
The shallow groundwaters are mainly fresh and locally slightly brackish, with the corresponding water types being Ca-HCO$_3$ and Na-Cl and the pH of the samples varying from 5.1 to 8.0. The samples collected since the earlier reports confirm the previous understanding of the hydrogeochemical system, and also show evidence of fresh water leakage from the Korvensuo reservoir.

11.1.2 Lithology, alteration and ductile deformation

The site lithology, i.e. the occurrence and distribution of rock types, as well as the alteration and ductile deformation of the rock, reveals important aspects of the structure of the site. Furthermore, it is directly related to the potential for mineral resources, or rather their lack, as well as to the thermal, rock mechanics and migration properties of the intact rock.

Lithology

Olkiluoto is located in the southern Satakunta region, i.e. in southwestern Finland. The crystalline bedrock of Finland is part of the Precambrian Fennoscandian Shield and the central and southern parts of Finland contain Early Palaeoproterozoic metamorphic and igneous rocks, belonging to the Svecofennian Domain. This domain was developed between 1930 Ma and 1800 Ma, either during one long Svecofennian orogeny, or during several, separate orogenies. Later the crust was intruded by Mesoproterozoic anorogenic rapakivi granites, 1650 – 1540 Ma in age. The youngest basement rocks in this part of Finland are the so-called Jotnian sandstones, ca. 1400 – 1300 Ma in age, and 1270 – 1250 Ma old olivine diabase dykes. The bedrock was eroded almost to its present level before the beginning of the Cambrian (about 600 million years ago). Due to erosion and continental conditions, it is almost totally lacking in sedimentary rocks younger than the Precambrian.

The bedrock of Olkiluoto comprises mainly high-grade metamorphic supracrustal rocks, the source materials of which are epiclastic and pyroclastic sediments. These rocks are migmatised by abundant leucocratic pegmatitic granites and cut by a few narrow mafic dykes. In terms of their mineral composition, texture and migmatite structure, the rocks of Olkiluoto can be divided into four major classes:

- migmatitic gneisses,
- tonalitic-granodioritic-granitic gneisses,
- other gneisses, including mica gneisses, quartz gneisses and mafic gneisses and
- pegmatitic granites.

The current 3D lithological model of the Olkiluoto site area consists of different gneiss units, pegmatitic granite units and diabase dykes, see e.g. Figure 11-1; with further detail being provided in Chapter 4.
Figure 11-1. Modelled pegmatitic granite units within the Olkiluoto site (taken from Figure 4-23 in Chapter 4). The other rock units are different gneisses and a few diabase dykes.

**Ductile deformation**

On the basis of refolding and cross-cutting relationships, the rocks have been subject to five stages (D1-D5) of polyphase ductile deformation. At Olkiluoto, the lithological layering and weak foliation created by the first phase of deformation (D1) are often (sub)parallel and represent the oldest observed structural elements. Deformation phase D2 is locally the most intensive phase and produced strong migmatisation, pervasive foliation and thrust-related folding. In the subsequent thrust-related deformation phase D3, the earlier-deformed migmatites were locally refolded, rotated or sheared. Subsequently, D3 elements and earlier structures were again re-deformed in deformation phase D4, which produced close to open folds with axial planes striking NNE and dipping to the ESE. Probably the youngest stage of ductile deformation is D5, the fold structures of which can be detected as small flexures or as outcrop-scale undulations of earlier-formed planar elements.

The main focus of the ductile deformation model is on the identification of structural domains, which can be considered “statistically homogeneous” with respect to a particular parameter or group of parameters (in this case the orientation of the foliation and the axial planes and the interpreted deformation intensity of a specific deformation phase). The interpreted structural domains, related to the orientations of the axial surfaces and the rarely-developed axial surface foliations of phases D3 and D4, are shown in Figure 4-25.

Based on the occurrence of the products of the deformation phases, Olkiluoto Island can be divided into tectonic sub-domains, which are also clearly observable, e.g. in the ground geophysical map, see Figure 11-2. The 3D ductile deformation model follows this division of the bedrock into northern, central and southeastern sub-domains.
**Figure 11-2.** Tectonic sub-domains of the Olkiluoto site, as shown on the ground geophysical (magnetic) map (from Figure 4-17).

**Alteration**

The bedrock at Olkiluoto has been subjected to extensive hydrothermal alteration processes, which are estimated to have taken place at temperatures from slightly over 300°C down to 50°C (Gehör et al. 2002). Based on the grade of alteration, two different types of hydrothermal alteration can be distinguished, a fracture-controlled type and a pervasive (or disseminated) type. The fracture-controlled alteration indicates that hydrothermal fluids have passed through the rock along planar features, with the alteration being restricted to incipient fractures or narrow zones adjacent to them. The pervasive alteration indicates the strongest type of alteration. It occurs as spots or is finely disseminated throughout the rock and in the fracture fillings.

Illitisation, kaolinisation and sulphidisation, both of the fracture-controlled and pervasive type, are the most prominent alteration events in the site model area. The alteration model shows the occurrence and distribution of the most pronounced alteration volumes of illite, kaolinite and sulphides at Olkiluoto. The alteration volumes (i.e. the modelled solids) are defined so as to encompass the volumes of strongest alteration and as many of the altered drill core sections as possible; however, they also include a lot of rock which displays only slight alteration or no alteration at all.

The alteration volume of sulphides is located in the uppermost part of the model volume, and is oriented roughly parallel to the lithological trend (i.e. dipping slightly SE). The alteration volume of kaolinite is also located in the uppermost part of the model, but has a shallow dip to the N. The alteration volume of illitisation, consists of two distinct volumes, see Figure 11-3. These alteration volumes lie one on the other, converge towards the northwest and are spatially associated with site-scale thrust faults. Calcite occurs as fracture infillings and as stockwork vein sets in the same bedrock volume as the other three hydrothermal alteration zones, and at least part of that is understood to present carbonatisation, which, however, has not affected the rock itself.
11.1.3 Rock mechanics and thermal properties of the intact rock

The strength and deformation properties of the intact rock, as well as its thermal properties, affect the rock’s stability, spalling in particular, and the potential for dissipating the heat produced in the spent fuel, respectively. These properties depend essentially on its intact rock mineral composition and structure. The rock mechanics and thermal property models are thus strongly linked to the site lithology, the alteration of the rock and the extent and form of the ductile deformation.

Strength

Following the progress reported in SR2006 (Andersson et al. 2007), the work has been focused on the intact rock strength, because this, together with the rock stress, is a key issue when predicting rock spalling. The mechanical properties of intact rock, i.e. the visually unfractured rock, can, in general, be characterised by the complete stress-strain curve, which is established by using standard test methods and procedures, as suggested by the International Society for Rock Mechanics (ISRM). The rock samples are tested under controlled conditions; however, in reality, the behaviour of rock under loading depends on many factors, such as the loading conditions, the sample size, the degree of saturation, the loading rate and its past loading history. Therefore, the strength of intact rock at the tunnel scale, i.e. its spalling strength, is found to be considerably lower than the intact rock strength established from the testing of small laboratory samples.

Figure 11-3. Sections of pervasive (dark green) and fracture-controlled (light green) illitisation in drillholes. The two green (light green with inclusions of dark green) volumes indicate the occurrence of illitised bedrock blocks (from Figure 4-26).
In order to define homogeneous units for modelling rock strength and to explain the observed variations in strength, lithological units, the type and degree of foliation, geophysical data and rock density data have been used. The following is found from this data assessment:

- As discussed in Chapter 4, the Olkiluoto area is divided into lithological units, but at the tunnel scale the rock is heterogeneous and the type and degree of heterogeneity changes rapidly. Based on the lithology, only the pegmatite, which represents about 20% of the rock types at Olkiluoto, can be separated in terms of its strength, having a mean tensile strength that is 55% lower than the other metamorphic rock types (but only 22% lower based on the preliminary ONK-PP68 results). The ranges of the other strength and deformation parameters of pegmatite lie within the variations of these parameters for the other metamorphic rock types.

- When considering the combined type and intensity of the foliation, a slight trend can be seen between the uniaxial compressive strength and the foliation. The magnitudes of the tensile strength, the crack damage stress and the peak strength are dominated by the orientation of the foliation, in a manner that would be expected from theoretical considerations, whereas the magnitude of the crack initiation stress is dominated only by the favourably-oriented weakest minerals.

- The first few tests (point load and laboratory tests) on altered rocks have not indicated significant strength differences between altered and fresh rocks.

Based on the fact that the rock type at Olkiluoto is very heterogeneous and that the type and degree of foliation are changing rapidly, the metamorphic rock types can be considered in this context as one rock domain (type) (i.e. migmatitic gneiss), with only the pegmatitic granite being considered a separate rock type.

For the metamorphic rocks, the variation of all of the key strength stress states is considerable, see Figure 11-4.
Figure 11-4. Variation of critical stress states of Olkiluoto metamorphic rock (from Figure 5-11).

Thermal properties

The thermal properties of a rock are controlled by its mineral composition, the thermal properties of the minerals, the texture of the rock (its anisotropy), its porosity, the pore fluids present, and the temperature and pressure. The thermal properties investigated at Olkiluoto include: thermal conductivity, specific heat capacity, thermal diffusivity, density and thermal expansion coefficient. These properties have been investigated using several techniques, including laboratory measurements of drill core samples, the theoretical estimation and modelling of thermal properties, as well as in situ measurements in drillholes, with instruments especially designed for the purpose.

Most of the data are laboratory measurements, made using drill core samples. The applied samples represent mostly migmatitic gneiss, but also tonalitic-granodioritic-granitic gneisses, and granite and pegmatite have also been included. In situ measurements with the TERO downhole tool have been reported from two drillholes. Thermal conductivities and diffusivities measured in situ and in the laboratory are in reasonable agreement, allowing for uncertainties due to differences in sampling volumes, unavoidable rock heterogeneity, as well as methodological issues.

The main focus of the thermal property studies has been the veined gneiss. The main minerals of the veined gneiss are quartz, plagioclase and biotite; however, its compositional variation is considerable, and the small size laboratory samples show the expected scatter of values. The constituent minerals of veined gneiss are thermally anisotropic, and the schistose and gneissic texture of the veined gneiss further enhances its anisotropy, see Figure 11-5. At the larger scale of metres to tens of metres, the structural anisotropy, caused by the migmatitic layering of the micaceous and felsic rock types, is also expected to generate a larger-scale thermal anisotropy.
Laboratory measurements on granite and pegmatite show thermal property values generally higher than those of the migmatitic gneiss. Data on granodiorite (tonalite) are limited, but indicate a lower range of conductivities. The database is too small to conclude anything definite about the anisotropy of granite and pegmatite, but the values show an anisotropy of the order of 20%. For tonalite, no laboratory data exist on anisotropy.

The thermal properties of rocks are temperature-dependent. Thermal conductivity and diffusivity decrease with increasing temperature, whereas specific heat capacity increases with increasing temperature.

**Figure 11-5.** Dependence of thermal conductivity and angle of schistosity/gneissic layering in drill core samples of the Olkiluoto veined gneiss (from Figure 5-40).

11.1.4 Brittle deformation

There are several reasons why it is important to understand the brittle deformation characteristics of the rock, as the large brittle deformation zones are potentially mechanically unstable and constitute the main transmissive elements of the rock mass. Fracturing at all scales affects the mechanical stability of the rock mass and provides potential paths for groundwater flow and solute migration.

**Brittle deformation zone model**

According to the observations from the ONKALO tunnel and from outcrops, the faults at Olkiluoto are either gently SE-dipping thrust faults or approximately N-S or NE-SW striking strike-slip faults, both types representing reactivated, earlier, non-brittle features. The fault zones can be conceptualised as consisting of one or more fault core zone(s) with a zone of influence adjacent to the core (see Chapter 4 for a discussion of...
these concepts). The zone of influence is generally known as a damage zone in the scientific literature (cf. Milnes et al. 2006).

Fault cores consist typically of non-cohesive or poorly-cohesive breccias and gouges and an increased numbers of slickensided surfaces and are typically heterogeneous in nature, having discontinuous, en echelon type of geometries, with anastomosing and branching traces. This heterogeneity may also lead to the existence of multiple fault cores within one fault zone intersection. The thickness of the core(s), as well as the relative proportions of fault breccia, fault gouge and the number of slickensides, can vary considerably from one intersection to another.

On each side of the fault core, and between potentially multiple cores, are zones of influence, in which the deformation during movement was less intense than in the fault core zone(s), with the intensity gradually vanishing towards the outer margins of the zone (Figure 11-6). The zones of influence are often indicated by geophysical anomalies (particularly on acoustic logs, Long Normal and Short Normal resistivity logs) and are generally more hydraulically conductive than averagely fractured rock (and often contain more transmissive fractures than the fault core itself). In a similar manner to the fault core, the zones of influence may vary considerably (on a metre to 100 metre scale) and also display variations in their internal properties from one location to another.

Subsidiary faults, which are typically closely associated with large fault zones, may be located close to the main fault zone and even within the zone of influence itself, but from drillhole data it is difficult to know whether these features are splays of the main fault zone or represent isolated features. Nevertheless, these subsidiary faults are presented here as an example of the complex and heterogeneous nature of fault zones.

**Figure 11-6.** Conceptual model of the structure of a single fault zone (from Figure 4-19).
A detailed description of the brittle deformation zone model is given by Mattila et al. (2008). However, a number of important changes and additions have been made to this Geological Site Model Version 1.0, as further described in Chapter 4. The main reason for this is the increased focus on the eastern part of the Site Model volume. Since there are only a few drillholes in this area, geophysics (3D seismic survey) and lineament interpretation have played an important role in interpreting deformation zones.

The geometry of site-scale zones BFZ018, BFZ056, BFZ098, BFZ080, BFZ099 and BFZ002 has been revised by re-examining all the drillhole intersections and by extending some of them to link up with interpreted lineaments on the ground surface and with seismic reflectors or electric conductors in the subsurface, see e.g. Figure 11-7. Furthermore, a number of lineament-based potential deformation zones have been added to the model, especially in the eastern part of the Site volume, although there are no direct geological observations for the majority of them. A group of subhorizontal or gently-dipping seismic reflectors have also been incorporated into the model.

![Figure 11-7. The modelled 3D geometry of OL-BFZ099 in the Geological Site Model version 1 is shown, together with depth-migrated seismic reflectors identified in the 2007 3D seismic survey. On this basis, OL-BFZ099 has been extended towards the SE, and to the bounding lineaments (from Figure 4-27).](image)

**Geological Discrete Fracture Network (DFN) model**

Fractures between the BFZ (Brittle Fracture Zones) are modelled statistically in a geological Discrete Fracture Network (DFN) model (Holmén et al. 2009). The geological DFN model provides a statistical description of fracture orientation, intensity and size. Furthermore, it should be noted that the geological DFN concerns all fractures, i.e. both open and sealed.

In order to account for differences in the fracturing in different parts of the rock, including any potential depth dependence, the rock is divided into different fracture
domains, each with its own DFN characteristics. In this first geological DFN study (Holmén et al. 2009), the proposed fracture domains are based on the description for the average orientation of the fractures, delimited by the geometry of zone OL-BFZ098 (“zone HZ20” in the hydrostructure model).

Three model alternatives have been developed, each one based on a different strategy of calibration. The models are calibrated against actual values of fracture frequency (P10) from drill cores and fracture trace intensity (P21) from the mapping of outcrops and tunnel walls. Given the amount of available information from the drillholes, the outcrops and the tunnel walls, different strategies were adopted for the calibration of the DFN model.

- For Model 1 the orientation and intensity descriptions are primarily based on the drillhole data, considering the uppermost fracture domain.
- For Model 2 a better match to the fracture intensity of the outcrops was desired and the intensity value was adjusted accordingly.
- For Model 3 the fracture size distribution was reviewed, based on the data from the ONKALO tunnel available by the end of 2007.

These three model alternatives are not equally probable. For example, comparing simulated fracture traces on the ONKALO tunnel wall with actually mapped fractures traces, suggests that Model 1, in particular, grossly overestimates the fracture frequency in the ONKALO (Figure 11-8); see also the discussion on the comparison between pilot hole and mapped data in Section 11.2.1 The DFN modelling, therefore, needs to continue, with more focus on the ONKALO data. Furthermore, the amount of available information on the fracture system at Olkiluoto will increase as the excavation of the ONKALO tunnel continues to greater depths. It follows that the DFN description provided in this document does not represent the final DFN description.
11.1.5 Mechanical properties of fractures, rock mass and BFZs

The mechanical properties of fractures, rock mass and BFZs are used as input to rock stability analyses for engineering purposes. The parameters are less important for long term safety.

Fractures

The stability of the rock mass is affected by the presence of fractures. For rock mechanics design it is the mapped fracture data that are used as input to the empirical Q system, which in turn can be used to assess the rock mass stability. For this reason the rock mechanics team has made their own assessment of the mapped fracture tunnel data from the ONKALO.

It is found that the number of fracture sets varies with tunnel chainage. Over the first 300 m, there can be three or more fracture sets present, which means that occasional or systematic rock blocks can be present. From chainage 300 m to about 1200 m, there are usually only two sets present and below chainage 1200 m there is essentially only one set present, plus a potential random component. Since block fall-out due to fractures can occur only when three or more fracture sets are present, such events could not occur below chainage 300 m. The geological DFN model has more sets. However, it should be noted that the rock mechanics interpretation of the tunnel mapping focuses on fractures that potentially could form rock block. It thereby excludes fractures with length less than 1 m and also excludes fractures terminating in intact rock. This procedure differs from geological DFN modelling, where all recorded observations are used in defining fracture sets (compare to Chapter 4). Furthermore, the interpretation of the major fracture sets is normally carried out for each 5 m long tunnel section, whereas the geological DFN is a statistical description of much larger volumes. Possibly, not all fracture sets of the DFN model occur at the same location. The mapped fracture data are
also used to estimate the fracture intensity (RQD value), the mapped fracture trace length and end type, and the values of fracture surface parameters Jr and Ja. For details, see Chapter 5.

In addition, a few direct tests have been conducted on fracture samples to establish their shear strength; however, there are as yet insufficient data to allow any overall conclusions to be drawn.

**Rock mass properties**

Rock mass parameters are assessed using empirical methods, and are based on intact rock strength and rock mass quality. The rock mass quality is based on the Q’ or GSI mapping of drillholes, pilot holes and tunnels.

After chainage 1300 m, the mean rock mass quality for each 100 m has been above Q’ = 100 (GSI = 85). Between chainage 2250-3120 m, there has been only one long section with Q’ less than 40 (GSI = 77), whilst the mean Q’ value is over 200 (GSI = 92). This generally implies Good, Very Good and Extremely Good rock mass qualities, although the strength of the intact rock itself may still be an issue.

In unfractured or sparsely-fractured rock, the in situ strength of the rock, i.e. its spalling strength, is estimated to be between the crack initiation and crack damage strengths. Using the mean values, this results in a spalling strength of 52-99 MPa for high-grade metamorphic rocks. Based on experiments from the Äspö HRL in Sweden and the URL in Canada (Martin and Christianson 2008), the spalling strength of the Äspö granodiorite and the URL granite is about 57% of the uniaxial compressive strength – with a corresponding mean value of 66 MPa for the metamorphic rocks at Olkiluoto, assuming the same relationship between spalling strength and uniaxial compressive strength as above.

**Brittle deformation zones**

Estimates of the mechanical properties of the brittle deformation zones are based on data from the Olkiluoto drillholes and from the ONKALO tunnel mapping. At this stage of reporting, ten brittle deformation zones have been analysed and the identification of the location and size of these zones is presented in Kemppainen et al. (2007). As described in that report, the properties of each zone are determined from those drillholes that penetrate the zone in question.

Determination of the strength and deformability properties is based on the rock mass classification technique. The strength and deformability properties of the brittle deformation zones were estimated via RocLab-software.

In order to determine the uniaxial compressive strength of the intact rock in a brittle deformation zone, point loads test were carried out. Only a limited number of tests have been completed on samples from the brittle deformation zones, but these indicate that there is no clear difference between the uniaxial compressive strength of the intact rock within and outside a zone. However, some limited testing has been performed using the Schmidt hammer, which suggests that the strength of the rock in the brittle deformation zone core to be about 11% to 20% of the strength of the intact fresh rock.
11.1.6 Rock stress

The in situ state of stress at Olkiluoto has been characterised using a description of the geological-tectonic history of Olkiluoto, information on regional stresses and direct and indirect stress measurement data from the site.

The major stress orientation in Fennoscandia can be attributed to an E-W direct compression from the mid-Atlantic ridge push and a N-S compression from the Alpine margin, thus resulting in a NW-SE orientation for the maximum horizontal stress $\sigma_H$. The stresses on Olkiluoto Island and for the ONKALO site may be perturbed relative to the regional stress state, due to the presence of faults and deformation zones; however, at this stage, there is no clear understanding of the possible influences of these zones on the local stress state. Moreover, stress estimations through direct and indirect methods indicate a relatively large scatter of both stress orientations and magnitudes, which may be related to local geological factors.

At the site scale, in situ stresses have been measured and/or estimated over a depth range of 29 to 985 m, using a variety of stress estimation methods. Indirect stress estimations are provided through Kaiser Effect measurements (the full stress tensor), core discing observations (horizontal stress magnitudes), and borehole breakouts (horizontal stress orientation).

Direct measurements (overcoring and hydraulic fracturing) have been carried out, both in vertical drillholes drilled from the surface, as well as in sub-horizontal drillholes drilled from the ONKALO ramp. Recently, measurements of the deformation response (through convergence measurements) of the shaft excavation (through raise boring), as well as local overcoring at the completed shaft perimeter (coupled with back-calculation), provided a larger-scale stress estimate of the horizontal stresses (their magnitude and orientation).

The data set of stress estimations has been evaluated, based on a re-analysis and ranking of older overcoring measurements and a ranking of recent overcoring measurements, core discing estimates and Kaiser Effect stress determinations. This evaluation concluded that a number of data points should be discarded. The collected data were also analysed in a semi-integration study (Ask, expected 2009), in which the raw data were re-evaluated and then a set of constraints applied to check their consistency.

In summary, the following conclusions can be stated regarding the in situ state of stress at Olkiluoto.

- A thrust faulting stress regime is present, i.e. the horizontal stresses are larger than the vertical stress, $\sigma_H > \sigma_h > \sigma_v$. Also, the principal stresses are oriented horizontally and vertically, respectively.

- On the regional scale, the maximum horizontal stress component is oriented NW-SE (146° as inferred from relative plate motions) but the data suggest a maximum horizontal stress orientation of N-S for the upper portion of the rock mass (0–300 m) and E-W for the lower portion of the rock mass (300–900 m).

- For the maximum and minimum horizontal stress, a bi-linear stress model is proposed, per the above (Figure 11-9).
Figure 11-9. Bi-linear stress model of Olkiluoto. Magnitude and orientation of $\sigma_H$ (the maximum horizontal stress also being the major principal stress) (compiled from Figure 5-6).

11.1.7 Hydrogeological properties

The groundwater flow, being a function of the hydraulic driving forces and the permeability distribution of the rock, is of key importance for safety, as the flow could effect the evolution of the groundwater composition and offers the only significant potential pathway for radionuclides that are released from the engineered barriers (EBS). The hydraulic properties depend on the fracturing of the rock, i.e. on the hydraulic properties of fractures and deformation zones, and how these are connected in space. The properties are described at different scales. The site-scale flow model is used to describe the past evolution of the site and the near-future hydrogeological impact of the ONKALO. The detailed-scale model, on the other hand, is amenable to describing the distribution of groundwater flow in the immediate vicinity of the planned spent fuel repository and the deposition holes for the waste canisters.

Site-scale model

The site-scale model focuses on the most extensive and transmissive features in the rock, referred to as hydrogeological zones (HZs), and describes these deterministically,
whereas the rock mass between these zones is described as a porous medium. Such a site-scale model was presented in SR2006 (Andersson et al. 2007), where it was shown that the majority of the transmissive fractures at depth could be located within the three gently-dipping HZs (HZ19 to HZ21), that are generally, although not fully, coincident with the system of gently-dipping brittle deformation zones, see Figure 11-10. There are transmissive fractures between these zones, but their frequency is substantially lower than inside the HZs, see Table 11-1.

**Figure 11-10. Basic hydrostructure model of Olkiluoto**

This model has now been updated, considering:

- The updated geological site model, described in Chapter 4, which represents a major revision from the previous model of Site Description 2006 (Andersson et al. 2007).
- Information from the nine new drillholes that has become available since the previous site model.
- Inconsistencies remaining after the hydrogeological flow model presented in SR2006, that are to be explained with proper adjustments in the model properties and the initial state.
- The more detailed scale ONKALO area model described by Kemppainen, Ahokas & Ahokas (2007).
In this update, fracture transmissivity and evidence of connectivity are the main parameters, which are used for determining the existence of a hydrogeological zone in a drillhole, except for the intensively-fractured zone HZ21 located below the planned repository level. Zone HZ21 was originally modelled on the basis of engineering geology, hydrogeological connections and geophysics, and its updating is based on the same types of information.

The main principle in determining the width of a hydrogeological zone in a drillhole is to attempt to include all highly transmissive fractures within such a zone, with the upper and lower surfaces of the zones following defined drillhole intersections. In the rock volumes within the central part of the Island, the zones are interpolated between the drillholes, whereas their extension outside this volume is by extrapolation. Most of the zones are assessed as being limited in extent and, therefore, any such extrapolation is over relatively small length scales. There are essentially three reasons for limiting the modelled extent of the zones: 1) higher drawdowns than expected, based on an infinite radial flow field along the confined aquifer (i.e. the HZ itself) during the pumping tests; 2) conceptual tectonic sub-domains and observed differences in the hydrogeological properties, e.g. total transmissivities of the drillholes and pressure responses between the drillholes; and 3) the results of the numerical flow modelling with the extended zones of the 2006 model (Andersson et al. 2007). If there are no indications for restricting the size of a HZ, it is extended so as to intersect the boundary lineaments.

The main hydrogeological zones, see Figure 11-12, introduced in the 2006 model remain, but some revisions, essentially regarding their geometries and properties, have been made. The main changes are as follows:

- The geometry of HZ19 is adjusted to fit exactly with the drillhole intersections and its extent is reduced and is limited to the central part of the island (called the WCA in the hydrogeological modelling), based on data from new drillholes to the northeast and east (OL-KR40, OL-KR41, OL-KR45, and OL-KR46).
- The description of the HZ20 system has been simplified, so as to include only zones HZ20A and HZ20B in this version, which relate to the upper and lower surfaces of the interpreted direct hydraulic connections between drillholes.
- In this model update, hydrogeological zone HZ21 has been relocated and extended to greater depth and also to the surface (Figure 6-12). Hydrogeological zone HZ099, in turn, has been greatly reduced in size, as has HZ001.
- HZ004 did not have a corresponding site-scale brittle deformation zone in the previous version of the model, but was based on geophysical data. In the updated geological model several sub-vertical geological deformation zones, e.g. OL-BFZ012, OL-BFZ013, and OL-BFZ053, are now modelled as being in the same rock volume.

The hydrogeological zone system HZ19 is intersected by many drillholes, allowing the measurement of a large number of associated transmissivities. The measured values show a few remarkably high transmissivities, as high as $10^{-4}$ m$^2$/s, while several values greater than $10^{-5}$ m$^2$/s are also present (Figure 6-6). These very high transmissivities underline the hydrogeological significance of the HZ19 zone system, leading to the effective transmissivities (geometric means) of $8\times10^{-5}$ m$^2$/s, $4\times10^{-5}$ m$^2$/s, and $3\times10^{-6}$ m$^2$/s for HZ19A, HC19C, and HZ19B, respectively.
A large number of transmissivity measurements are also associated with hydrogeological zone HZ20. A large number of the measured values are of the order of $10^{-5}$ m$^2$/s, or greater than $10^{-6}$ m$^2$/s, leading to effective transmissivities of $5 \times 10^{-6}$ m$^2$/s and $3 \times 10^{-6}$ m$^2$/s for HZ20A and HZ20B, respectively.

The measured transmissivities associated with HZ21 and HZ099 are lower, but the variability of the values are of similar magnitude. High measured transmissivities are associated with hydrogeological zone HZ001 to 200 m depth; and in the current model there is only one, but clearly lower, transmissivity at greater depth. The measured transmissivities lead to the effective values of $1 \times 10^{-8}$ m$^2$/s, $2 \times 10^{-7}$ m$^2$/s, and $1 \times 10^{-6}$ m$^2$/s for hydrogeological zones HZ21, HZ099, and HZ001, respectively.

An essential part of the groundwater flow analyses is calibration, which strives to ensure that the flow model corresponds to the hydraulic characteristics of the real system as much as possible. The flow model that gave the best agreement with the baseline field data (pumping test responses, pressure, salinity) was chosen to be used for both the characterisation of the natural groundwater flow conditions prevailing before the excavation of the ONKALO and the prediction of the hydrogeological impacts of the ONKALO. On the basis of the adopted three-step manual calibration process, the following measures were taken:

- the transmissivities of seven hydrogeological zones (HZs) were modified (with related adjustments to the flow porosities, based on the cubic law)
- the alternative with slightly lower values at depth was selected for the effective hydraulic conductivity of the sparsely fractured rock (SFR),
- an anisotropic hydraulic conductivity (horizontal/vertical ratio of 10) was used in the uppermost 50 m of the sparsely fractured rock
- the diffusion porosity in the salt transport model was increased from 0.2% to 1%
- instead of starting the simulations at the early Littorina Stage (8000 years BP), the final results were obtained by starting the simulations at 2800 years BP, assuming a constant initial TDS of 8 g/L down to a depth of 360 m.

In the final model, the calculated drawdowns in all the pumped sections, as well as the pressures in the deep drillholes, show a satisfactory agreement with the actual measured values, see e.g. Figure 11-11, although some local discrepancies still remain in single drillhole sections. By starting the simulations from 2800 years BP, (the approximate time when the highest point of Olkiluoto Island rose above sea level), by adjusting the parameters affecting the infiltration and the time scales of solute transport it was also possible to prevent the fresh water from flushing out the brackish water from the upper part of the modelled volume onwards. Having taken all the actions listed above, the calculated TDS agree well with the observations in the drillholes, see e.g. Figure 11-11.
Figure 11-11. Comparison between measured and simulated pressure and salinity for various steps in the calibration process.

The question can be raised as to what would be required to resolve the remaining discrepancies between the calculated results and the observations. It is questionable whether it is worthwhile to try to reproduce each single local observation with the flow model, which has been designed for the site-scale description of the evolution and dynamics of the groundwater conditions. The site-scale geometry of the hydrogeological zones does not contain all the known small-scale hydraulic connections, and thus with the HZs constituting practically the only heterogeneity in the flow model, the model may simply be too coarse to capture all the observations originating from the smaller-scale features, especially the few single high TDS observations at shallow depths, which have proved to be difficult to reproduce.

**Hydrogeological DFN**

A more detailed description of the hydraulic properties of the rock is provided by the hydrogeological DFN model. This is a site-scale model that contains both stochastic and deterministic features, see Section 6.6. The approach combines a deterministic representation of the hydrogeologically-active deformation zones (HZ), as provided in the site-scale model presented above, with a stochastic representation of the sparsely fractured bedrock outside these zones, using a hydrogeological discrete fracture network (the Hydro-DFN) concept. The HZ and Hydro-DFN models are parameterised hydraulically, mainly using data from single-hole Posiva Flow Log (PFL) measure-
ments. In a few cases the results of single-hole long-term pumping tests and double packer (HTU) tests have also been used.

The bedrock within the Olkiluoto site area is represented by two fracture domains, as suggested by the geological DFN modelling. In the Hydro-DFN model these domains are separated by HZ20 in the central part of the island and by an imaginary extension of HZ20 that follows the plane of HZ20 outside the central part of the island. The bedrock above zone HZ20A, or its extension, is referred to as the ‘fracture domain above’ (FDa) and bedrock below zone HZ20B, or its extension, as the ‘fracture domain below’ (FDb).

Fracture data analysis is based on the measured data from the drillholes. Fracture transmissivities are determined with the PFL, and the associated fracture locations and orientations are determined from drill core mapping and/or borehole TV images. A systematic mapping of the fractures using the PFL is performed in the sub-vertical KR and KRB surface drillholes and in the sub-horizontal PH tunnel pilot holes. Most of the KR and KRB drillholes data, and all data from the PH holes, are from fracture domain FDa, see Figure 11-12. There are 46 005 fractures in the primary fracture database and, of these, 2188 records are defined as PFL fractures.

Figure 11-12. Visualisation of the boreholes and the positions of the PFL data. Fracture domain FDa occurs above the highlighted zones HZ20A and HZ20B, whereas fracture domain FDb occurs below. View towards the southwest.

Analysing the intensity of the PFL data shows that the intensity of (i) all the fractures and (ii) the PFL fractures is much greater in the hydrogeological zones than in the two fracture domains. Furthermore, the frequency of the PFL fractures significantly decreases with depth. Fairly homogeneous sub-volumes, with regard to the depth trend of the corrected PFL fracture intensity, can be produced by subdividing each fracture domain into four depth zones DZ1-4, see Table 11-1.
Table 11-1. Summary of flowing fracture frequency and transmissivity statistics (PFL fractures) for different depth zones (Compiled from measurements in the KR and KRB drillholes), where $P_{10, \text{all}}$ is the total fracture frequency, $P_{10, \text{open}}$ the frequency of open fractures and $P_{10, \text{PFL}}$ the frequency of fractures showing flow in the PFL logs. $\Sigma T_{\text{PFL}} / \Sigma BH$ length is the sum of all fracture transmissivities in a drillhole, divided by the length of the drillhole (Compiled from Table 5-4 in Hartley et al. 2008).

<table>
<thead>
<tr>
<th>Depth zone</th>
<th>1 (0 to –50)</th>
<th>2 (–50 to –150)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment</td>
<td>FDa FDb HZ</td>
<td>FDa FDb HZ</td>
</tr>
<tr>
<td>$P_{10, \text{all}}$, corr</td>
<td>3.77 4.64 7.25</td>
<td>3.17 4.48 7.36</td>
</tr>
<tr>
<td>$P_{10, \text{open}}$, corr</td>
<td>2.40 2.80 5.17</td>
<td>1.88 2.60 5.31</td>
</tr>
<tr>
<td>$P_{10, \text{PFL}}$, corr</td>
<td>0.50 0.60 1.28</td>
<td>0.24 0.30 0.92</td>
</tr>
<tr>
<td>$\Sigma T_{\text{PFL}} / \Sigma BH$ length</td>
<td>2.07E-07 3.62E-07 9.49E-06</td>
<td>1.03E-07 3.92E-08 4.92E-06</td>
</tr>
<tr>
<td>Max $T_{\text{PFL}}$</td>
<td>6.03E-05 4.94E-05 1.63E-04</td>
<td>1.24E-04 9.42E-06 1.01E-04</td>
</tr>
<tr>
<td>Min $T_{\text{PFL}}$</td>
<td>5.21E-10 2.95E-10 2.76E-09</td>
<td>1.55E-10 3.16E-10 1.18E-09</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth zone</th>
<th>3 (–150 to –400)</th>
<th>4 (–400 to –1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment</td>
<td>FDa FDb HZ</td>
<td>FDa FDb HZ</td>
</tr>
<tr>
<td>$P_{10, \text{all}}$, corr</td>
<td>2.04 2.65 9.40</td>
<td>1.20 1.88 8.40</td>
</tr>
<tr>
<td>$P_{10, \text{open}}$, corr</td>
<td>1.25 1.58 6.18</td>
<td>0.71 1.08 4.82</td>
</tr>
<tr>
<td>$P_{10, \text{PFL}}$, corr</td>
<td>0.05 0.08 0.58</td>
<td>0.00 0.02 0.24</td>
</tr>
<tr>
<td>$\Sigma T_{\text{PFL}} / \Sigma BH$ length</td>
<td>1.99E-08 9.52E-09 2.48E-06</td>
<td>1.28E-10 1.66E-09 2.43E-07</td>
</tr>
<tr>
<td>Max $T_{\text{PFL}}$</td>
<td>2.96E-05 1.68E-05 1.28E-04</td>
<td>3.09E-08 6.23E-06 1.41E-05</td>
</tr>
<tr>
<td>Min $T_{\text{PFL}}$</td>
<td>2.04E-10 3.31E-10 2.03E-09</td>
<td>- 5.01E-10 1.19E-09</td>
</tr>
</tbody>
</table>

Two alternative models are used to represent fracture sizes. Case A uses a power-law size model, whereas Case B uses a log-normal size model. Fracture size parameters have been determined in the Hydro-DFN flow simulations by matching the simulated and measured PFL fracture intensities. The uncertainty in the Hydro-DFN model, that is related to the uncertain ratio of the potentially water-conducting and flowing fractures along the drillholes, is assessed by these alternatives. Case A assumes a high frequency of potentially water-conducting fractures and Case B a low frequency of these fractures. In addition, there are uncertainties related to the correlation between fracture size and transmissivity. This is taken into account by considering three different fracture size-transmissivity models.

The Hydro-DFN models have been calibrated by comparing simulated and observed fracture statistics to the abstraction drillhole, by considering the average flow rate over the DFN realisations to the drillhole divided by the drawdown (notated Q/s), the
statistics of log(Q/s) for the inflows within each fracture set taken over all realisations and the average numbers of PFL fractures.

The connected open fracture size distribution in both fracture size models approaches the generated fracture size distribution for sufficiently large fracture sizes. However, the current fracture size distribution parameters for the log-normal size distribution produce a higher proportion of large connected fractures (50 m) and fewer connected small fractures (10 m) compared with the power law size distribution, Figure 11-13.
<table>
<thead>
<tr>
<th>Size distribution</th>
<th>A slice through open fracture generated</th>
<th>A slice through connected open fractures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power-law</td>
<td><img src="image1" alt="Power-law Diagram" /></td>
<td><img src="image2" alt="Power-law Diagram" /></td>
</tr>
<tr>
<td>Log-normal</td>
<td><img src="image3" alt="Log-normal Diagram" /></td>
<td><img src="image4" alt="Log-normal Diagram" /></td>
</tr>
</tbody>
</table>

**Figure 11-13. Illustration of fracture connectivity for Case A and Case B models (from Figure 6-38).**

The strong depth dependency in the flowing fracture frequency is also reflected in the up-scaled block conductivities. Simulated up-scaled 50 m block conductivities show a fraction of percolation that is around 40% or less in the deepest depth zone DZ4. The mean simulated effective hydraulic conductivity for the flowing 50 m blocks is about
two orders of magnitude smaller in the deepest depth zone than in the uppermost zone. The simulated median ratio of the anisotropy for the up-scaled hydraulic conductivity for the 50 m block size is around 8 for the depth zone from 0 m to -50 m and over 20 below the -400 m level.

Comparison of the three different fracture transmissivity-size models show that it has been possible to find parameters for the relationships between transmissivity and fracture size for all model variants that give an acceptable match to observations. However, Case A, with power-law fracture size distributions and a semi-correlated fracture size-transmissivity model, is regarded as being the most physically realistic.

11.1.8 Hydrogeochemistry and its past evolution

A favourable groundwater composition is an essential safety function of the geosphere. As part of the site characterisation programme it is necessary both to characterise the current composition of the groundwater and to assess the processes controlling its composition. These two elements also provide the basis for modelling its future evolution.

The hydrogeochemical model is based on the chemical, isotopic and microbiological data of water samples and minerals, and geochemical modelling in conjunction with knowledge of the hydrogeological and geological features of the site. The interpretation of baseline conditions and the evolutionary processes supplements the geochemical concept presented by Pitkänen et al. (2004), Pitkänen & Partamies (2007) and Andersson et al. (2007). Groundwater samples from new drillholes support the earlier concept, thus indicating the strength of previous hydrogeochemical model. Investigations of matrix pore waters and monitoring from old drillholes, however, highlight uncertainties and local details, which require further studies and integrated considerations of the hydrogeological and hydrogeochemical evolution.

The hydrogeochemical conditions in the bedrock and their distribution are the result of progressive mixing and reactions between various initial water types, which represent some of the major events at the site during its geological history. The changes in climate and the geological environment have had a significant effect on local palaeohydrogeological conditions, which in turn have permitted infiltration and evolution of specific end-member waters in the bedrock. In addition, water-rock interaction caused by weathering processes during infiltration plays a major role in increasing the input of solutes in shallow groundwater. Figure 11-16 at the end of this section, presents an overview of the current understanding of the groundwaters at Olkiluoto.

Groundwater composition

The groundwater chemistry over the depth range 0-1000 m at Olkiluoto is characterised by a significant range in salinity, see Figure 11-14. Fresh groundwater with low total dissolved solids (TDS ≤ 1 g/l) is found only at shallow depths, in the uppermost tens of metres. Brackish groundwater, with TDS up to 10 g/l dominates at depth, with TDS values varying from 30 m to 450 m depth. The fresh and brackish groundwaters are classified into three groups on the basis of their characteristic anion contents, which also reflect the origin of salinity in each groundwater type. In all, four groundwater types can be identified:
- Fresh/Brackish $\ce{HCO_3}$ type
- Brackish $\ce{SO_4}$ type
- Brackish $\ce{Cl}$ type
- Saline

Chloride is normally the dominant anion in all bedrock groundwaters, but the near-surface groundwaters are also rich in dissolved carbonate (high DIC in Fresh/Brackish $\ce{HCO_3}$ type). The intermediate layer (100-300 m) is characterised by high $\ce{SO_4}$ concentrations (Brackish $\ce{SO_4}$ type) and the deepest layer solely by $\ce{Cl}$ (Brackish $\ce{Cl}$ type), where $\ce{SO_4}$ is almost absent. In crystalline rocks high DIC contents are typical of meteoric groundwaters, which have infiltrated through organic soil layers, whereas high $\ce{SO_4}$ contents in a crystalline rocks without $\ce{SO_4}$ mineral phases indicate a marine origin. *Saline groundwater* (TDS > 10 g/l) dominates below 400 m depth. The highest salinity observed so far is 84 g/L, which is actually below the limit generally used for brine (TDS > 100 g/L). Sodium and calcium are the dominant cations in all groundwaters and Mg is notably enriched in $\ce{SO_4}$-rich groundwaters, supporting their marine origin.

![Figure 11-14. Groundwater types of the baseline groundwater samples depicted in the Olkiluoto model presenting hydrogeological structures HZ19(A-C), HZ20(A and B) and HZ21. Cylinders show sampling sections in drillholes (note: long sections may represent several samples) and groundwater types: fresh/brackish $\ce{HCO_3}$ type is grey, brackish $\ce{SO_4}$ yellow, brackish $\ce{Cl}$ green and blue is saline. View approximately to north and deepest drillholes are approximately 1000 m long.](image)

The majority of the brackish $\ce{Cl}$ type groundwaters have been sampled from relatively low transmissive sections of drillholes, whereas other water types cover a much wider range of transmissivities. In addition, it seems that in high transmissive drillhole sections Littorina-derived $\ce{SO_4}$-rich groundwater has infiltrated, whereas in low transmissive rock slightly less saline brackish $\ce{Cl}$ type groundwater could have been...
conserved in pockets at similar depths to the SO\textsubscript{4}-rich groundwater. There has been insufficient time for intrusion of the Littorina-derived groundwater in these relatively tight fractures or for balancing the chemical disequilibrium between low transmissive and the major hydrogeological features by diffusion. These indications are further supported by EC (electric conductivity) data. In conclusion, brackish SO\textsubscript{4} and brackish Cl type groundwaters occurs partly at similar depths, but the former in high transmissivity and the latter in low transmissivity fractures.

**Pore water composition**

Matrix pore water chloride concentrations are less than 2g/L down to a depth of 420 m. In the present-day groundwater from fractures, such low concentrations are only observed in the shallow bedrock down to a depth of about 150 m, whereas they increase up to 10g/L at 420 m depth.

In the shallow parts of the Olkiluoto bedrock (0-150 m depth) matrix pore water seems to be in equilibrium with the adjacent fracture groundwater. The short distances between water-conducting fractures and pore water samples in this zone facilitate such steady-state conditions, and a similar origin for both water types could be suggested.

In the bedrock between 150-420 m depth a transient state is established for the Cl-concentration and $\delta^{18}$O ratios between pore water and fracture groundwater. The dilute state and the matrix pore water being enriched in $^{18}$O compared to adjacent fracture groundwater in this zone, suggests a long-term circulation of dilute (fresh) fracture groundwater under warm climate conditions, considerably longer than the more recent ingress of post-glacial seawater and meteoric water. The presence of $\delta^{18}$O signatures strongly enriched in $^{18}$O exclude a significant influence of glacial water on the pore water composition at these depths. This indicates that the time during which $^{18}$O depleted glacial water ($\delta^{18}$O ~ -22‰ V-SMOW) was present in the fracture system was too short and/or the recharge of this water type was probably hindered in its infiltration to such depth. It thus appears that the warm water component that is still present in the pore waters has a pre-glacial, possibly Tertiary origin.

The preservation of the dilute warm-climate meteoric water signature in the deeper part of the bedrock is consistent with the low fracture frequency and low-permeability and the large distances (≥ about 15 m) between pore water samples and groundwater at these depths. However, pore water in the almost fracture-free bedrock zone between about 150-420 m depth has lower chloride concentrations than these deepest pore water samples. The same chemical and isotopic pore water signatures are also preserved in samples collected from near-by water-conducting fractures (1.6 - 3.4 m). The reasons for the observed transient state in the deep groundwater system, i.e. deviations in salinities and stable isotope compositions as well assumed residence times between groundwaters and porewaters, are unclear at present. Further studies are underway in this area.

**Mixing and ongoing reactions**

Current groundwaters are mixtures of ancient end-member water compositions, which represent formation waters from certain geological conditions, such as Littorina seawater, glacial meltwater and original brine. The groundwater data contain reference samples that are the most extreme derivatives of those end-member waters. There have also been certain groundwaters representing intermediate stages, which occurred in the bedrock when hydrogeological conditions changed during deglaciation and postglacial
times, the influence of which is still observable in the compositions of conservative tracers.

Comparison of $\delta^{18}$O and Cl data, Figure 11-15, indicates four extreme reference groundwaters, which can govern the other groundwater compositions by mixing. The waters are, according to age, brine reference, glacial reference, Littorina reference and meteoric water which, with the addition of Baltic seawater (basically diluted Littorina seawater), enable the mixing traces of the other samples to be determined.

The four groundwater types form a layered, relatively horizontal 3-D structure in the bedrock fractures. HCO$_3$-rich and SO$_4$-rich groundwaters have infiltrated slightly deeper in major hydrogeological zones, but this layering of the groundwater types is also evident in them. In low transmissive rock, less saline brackish Cl type groundwater could have been conserved in pockets. There may not have been enough time for Littorina-derived groundwater to flow into these relatively tight fractures or, in particular, for a balancing of the chemical disequilibrium between low transmissive bedrock and major hydrogeological features to take place by diffusion. The hydrogeological variations during former glacial period have not been able to develop sufficiently high gradients to disturb the deep saline groundwater. Glacial water infiltration has been limited to 100 – 300 m depth at Olkiluoto and it has not influenced the chemistry of the pore water.

It is, however, also noteworthy that obvious mixing trends in the data cannot be described using reference waters alone. The linear dilution of saline groundwater could be solved by the mixing of two end-members - brine reference and fresh to brackish water with $\delta^{18}$O between -12 and -13‰. This fresh to brackish water could be a constant mixture of other fresh and brackish reference waters (or their original end-members). However, a high Br-Cl-ratio, extremely low HCO$_3$ and SO$_4$ contents and a mixing trend in stable isotopic composition of saline and brackish Cl-type groundwaters, indicate that these groundwater types do not contain postglacial water components, i.e. Littorina-derived seawater and meteoric recharge. Therefore, it can be assumed that saline groundwater has also not been diluted by pure glacial meltwater. The dilution of saline groundwater is, accordingly, due to an older event than the last deglaciation and may be the sum of several fresh water infiltrations of glacial meltwater, as well as of meteoric recharge, for example during earlier Quaternary glacial cycles.
Water-rock interactions, such as carbon and sulphur cycling and silicate reactions, buffer the pH and redox conditions and stabilise the groundwater chemistry. During infiltration, water-rock interaction caused by weathering processes plays a major role in increasing the input of solutes in shallow groundwater. Weathering processes induced by dissolved gases, i.e. CO$_2$ and O$_2$, typically dominate in shallow, low pH water, recharging through the organic soil layer into the inorganic overburden and bedrock. Soil air forms a significant source of these gases above the groundwater table and an open system equilibration with these gases enables a notable increase in DIC and SO$_4$ to take place during infiltration. Carbon dioxide is mainly generated by microbes in aerobic oxidation of organic carbon, which probably consumes the majority of the oxygen from recharging water below the groundwater table. Oxygen is also depleted slightly by biochemical activity during the oxidation of organic sulphur and CH$_4$ that is produced during the anaerobic decay of plant debris. The pH value is controlled by the sensitive equilibrium of dissolved CO$_2$ (carbonic acid) and its dissociation products (bicarbonate and carbonate ions) and fracture calcites. Carbon acid as a proton source is the major agent in weathering, dissolving minerals and increasing salinity during infiltration, which is observed when comparing groundwater data with the seawater dilution line.

The results cannot specify the actual sources dissolved that result in an increased salinity. Probably, the dissolution of calcite and silicates, such as plagioclase, K-
feldspar, biotite or their clayey alteration products are relevant. Cation exchange is evidently an important process in an aquifer which has been exposed to salinity changes by sequential meteoric and seawater intrusions. Cation exchange probably retards Ca and Mg enrichment at shallow depths, with Na being released to the groundwater. The former infiltration of marine-derived, \( \text{SO}_4^{2-} \)-rich groundwater has resulted in the uptake of Na and the release of Ca to the groundwater, whereas the exchange of Ca for Na should have dominated at greater depth.

Redox conditions at Olkiluoto have been considered to be anoxic, except in few cases in shallow infiltrating groundwater. This interpretation is also supported by the observations of scarce iron oxyhydroxides from fracture surfaces at greater than 10 m depth. Pyrite and other iron sulphides are instead common in fractures throughout the investigated range of depths, indicating a strong lithological buffer against oxic waters over geological time scales.

The hydrochemical, isotopic and microbial results strengthen previous interpretations of sequential redox zoning in the baseline hydrogeochemical system at Olkiluoto. The redox zones are characterised by the dominant redox species and they are controlled by the mixing interfaces of redox processes, which in theory transfer the mixing system from instability towards thermodynamic equilibrium. However, in low temperature environments, these reactions are not spontaneous and do not reach thermodynamic equilibrium. In reality they are kinetically controlled and are mediated by microbes, using organic matter, methane or hydrogen as energy source in reducing oxygen, sulphate or carbonate. Microbes do not necessarily totally deplete the reactants, due to energy thresholds and the low concentrations of reactants, which restrict microbial activity.

The hydrogeochemical system includes two natural metastable interfaces where the majority of chemical processes are concentrated, as well as the microbial activity (Figure 11-16). The upper is the infiltration zone, which lies mainly in the overburden, and the lower lies at 200 – 300 m depth, where \( \text{SO}_4^{2-} \)-rich groundwater changes to \( \text{SO}_4^{2-} \)-poor, but becomes methane-rich groundwater. At the upper interface oxic waters infiltrate into the organic-rich layer in the overburden and the degradation of organic carbon activates weathering processes. The oxygen consumption, together with iron oxyhydroxide and \( \text{SO}_4^{2-} \) reduction, seems to decrease the DOC content to a low level and stabilise the \( \text{SO}_4^{2-} \)-rich groundwaters internally. At the lower interface, between the sulphidic and methanic redox environments (which corresponds to brackish \( \text{SO}_4^{2-} \) and brackish Cl types), the instability of \( \text{SO}_4^{2-} \) and \( \text{CH}_4 \) in a common system results in the formation of dissolved sulphide and carbonate as reaction products. Methanotrophs oxidise \( \text{CH}_4 \) in aerobic conditions, but the detailed mechanism regarding the microbial use of \( \text{CH}_4 \) in anaerobic conditions is still unclear. The insolubility of iron sulphides (pyrite) depletes the ferrous iron pool, which causes the excess of dissolved sulphide which is occasionally observed. Calcite precipitation, due its acidic nature, may result in the minor dissolution of silicates in this zone. A high \( \text{CH}_4 \) concentration has great buffering capacity against oxidants diffusing/mixing in the deep groundwater system and has stabilised brackish Cl and saline groundwaters internally.

A slight enrichment of \( \text{H}_2 \) with depth may be controlled by the decreased activity of methanogens in producing \( \text{CH}_4 \) with very low DIC contents. The DIC content decreases with depth due to the increasing Ca content and the tendency to maintain calcite equilibrium. Major fractions of \( \text{H}_2 \) and \( \text{CH}_4 \) are probably abiogenic in origin at Olkiluoto. They may diffuse from rock pores and fluid inclusion and accumulate very slowly in groundwater.
11.1.9 Transport properties

The main retention processes that are considered in the transport analysis presented in Chapter 8 are matrix diffusion and sorption. Geosphere performance measures that are important for these retention processes are the distribution of flow (WL/Q) and rock matrix retention properties along the flow paths (porosity, diffusivity and Kd).

Immobile zones

Immobile zones are comprised of pore spaces in the rock mass that are saturated by water, but are not subject to flow. The identification of these immobile zones and their evaluation is based on the investigation of the hydraulic features in the drillhole cores. The physical properties of the immobile zones are characterised using samples that are taken from the cores, and a sufficient number of core samples is used in order to establish a comprehensive view of the immobile zones related to different hydraulic features. In practice, this comprehensive view is represented by a set of simplified models that describe the structures of the immobile zones (Figure 11-17).

The investigation and conceptualisation of the immobile pore spaces of the site-scale hydraulic features is currently under development and a complete set of the conceptualised fracture retention models (immobile zones and their retention properties)
is not available. Currently, matrix retention properties are based on the results of the rock matrix study carried out for boreholes KR38 and KR39 using the 14C-PMMA method. Porosity profiles in the rock matrix were measured from the autoradiographs taken from the surfaces of sawn rock samples. Typically, porosities range from 1% to 5% close to the fractures, see Figure 11-17, which from Archie’s Law, would correspond to diffusivities in the range of $5 \times 10^{-13}$ m$^2$/s to $5 \times 10^{-12}$ m$^2$/s. Major fracture-filling minerals are clay minerals, calcite and sulphides (31%). Fracture fillings are composed of different combinations of the major filling minerals, so that clay-filled fractures are the most common, followed by clay and sulphide, calcite or clay and lastly calcite filled fractures.

![Figure 11-17](image)

**Figure 11-17.** Conceptualised immobile zone retention models for the filled and non-filled background fractures. (Based on Figure 8-4).

More data are needed to enhance confidence in the immobile zone model. In situ measurements of rock matrix diffusivity and porosity will be carried out in the investigation niches of the ONKALO tunnel, as well as on core samples in the laboratory. Also, the sorption properties of radionuclides in the altered and unaltered rock matrix will be studied using core samples from representative drillholes. However, since sorption depends to a considerably greater extent on the (future) groundwater composition than on the mineralogy of the rock, it will be mainly assessed as a part of the safety case in the Model and Data report.

**Mobile zones**

Flow is usually very unevenly distributed between different hydraulic features in the fractured rock, leading to preferential flow paths and channelled solute transport at all scales. The modelling approach is to take hydraulic features into account explicitly at the different scales and to apply the appropriate spatial resolution in the different sub-
domains of the model. The applied modelling concept is based on a site-scale Hydro-DFN model, that is composed of hydraulic structures at the regional, site and fracture scales. The site-scale Olkiluoto Hydro-DFN model is introduced in Section 6.6 and summarised in Section 11.1.7. Flow and transport simulations have been performed using a detailed-scale DFN model of the repository near-field and a site-scale DFN model.

The repository near-field model is used to study possible differences in the flow and transport properties between different Hydro-DFN model variants and for different flow directions. The model domain is a cube with sides of 200 m, with the model including only stochastic background fractures. Simulations have been repeated separately for the two deepest depth zones that represent possible repository host rock.

The significant difference in the flowing fracture frequency between depth zones DZ3 and DZ4, see Table 11-1, is clearly reflected in the percentage of the deposition holes intersected by a flowing fracture. In DZ3, about 20% of the simulated deposition holes are intersected by a flowing fracture, whereas in DZ4 fewer than 5% of the simulated deposition holes are intersected by a flowing fracture. The difference in the flowing fracture frequency between the different alternative models is small and there is also no clear difference between their retention properties. In contrast, the variability between different realisations is large, especially in the case of the deepest depth zone DZ4. This follows from the very low number of connected flow paths per realisation in the sparsely-fractured DZ4 fracture network. In this respect, the most reliable results of this modelling are the median F values for depth zone DZ3 and the fact there is no statistically significant difference between alternative models. These results indicate that PFL measurements have a strong correlation with the retention properties, i.e. F along the flow paths. All alternative models are calibrated using the same PFL data and simulations show that they also appear to produce similar retention properties along the flow paths.

The site-scale model covers the whole of Olkiluoto Island and consists of large, deterministic hydrogeological zones and stochastic background fractures. The site-scale model is used to assess the transport properties of the release paths from potential canister locations. The transmissivity and geometry of the hydrogeological zones are based on the 2008 hydro-structural model. The boundary conditions applied in the simulations were no-flow on the base and on all vertical sides of the model domain and a specified head on the top boundary that matched the topography. The fractures were generated according to the Case A Hydro-DFN model parameters and using a calibrated, semi-correlated fracture transmissivity model (cf. Section 6.6).

Only a few percent of the release points are connected to the flowing fractures, as was also the case in the repository near-field simulations. The statistics of the retention properties studied from one realisation show a significant spread in the transport resistance WL/Q for the few connected paths, Figure 11-17. Furthermore, there seems to be a correlation between WL/Q and the initial water velocity at the start position, but a more limited correlation between the WL/Q and the transmissivity values of the initial fracture. The flow path with the smallest WL/Q appears to be group of flow paths with a high initial flow velocity.

The overall spread in the discharge locations is quite limited and is governed by the topography and the position of the shoreline. However, large stochastic features seem to play a more important role in determining the exact discharge locations than do the local deterministic zones.
Figure 11-18. Histogram of log(F), i.e. the same as log (WL/Q) for a single realisation of the site model with one particle per start position. (Figure 8-9 of Chapter 8). However, it should be noted that only a few percent of the release points are connected to the flowing fractures.

11.2 Predictability

Comparing predictions made using the Site Model, with the mapped or monitored outcome is important, both to test the maturity of the model and to assess how much detailed information is needed before a sufficiently precise prediction could be made regarding the conditions of a specific volume of rock. For this reason, two types of prediction/outcome studies have been undertaken:

Existing A predictions (i.e. made using Site Model 2006) are compared with more recent outcomes (which make use of pilot hole data, mapping or observed disturbances) and the results are used to assess whether there is a need to update the previous model. New A predictions will be made using Site Model 2008.

B-predictions, based on pilot holes, are used to assess the correlation between pilot holes and tunnel mapping at the deposition hole scale. The level of such correlation will be an important factor when making decisions about the suitability of a tunnel for waste disposal and will be an important input to the “DETECT” project of the RSC programme, as outlined in the 2006 R&D programme, described in TKS2006 (Posiva 2006).

11.2.1 Geology

As further discussed in Section 9.2, geological predictions and outcomes are compared for the ONKALO tunnel section from chainage 140 to 990 m. Generally, there is good to fair agreement between the predictions of the model and the outcomes for attributes such as lithology, ductile deformation and intersections with brittle deformation zones.
This applies both for predictions made using Site Model 2006 and predictions made using pilot hole data, which gives confidence, both in the Site Model and in the ability to make detailed predictions at the tunnel scale using pilot hole data. However, some important issues remain:

- The predictions of lithology and the results of the tunnel mapping seem to correspond fairly well, yet a clear discrepancy exists regarding the resolution of the data presented in the predictions, based on pilot hole data, and the outcome. The pilot hole-based predictions provide a very detailed description of probable conditions in the tunnel, and it is unclear whether the predicted lithological units actually exist in the tunnel, but were excluded from the outcome due to their limited dimensions, or whether the predictions themselves are incorrect.

- As the mean orientation of the foliation is known to be relatively constant at Olkiluoto, it is no surprise that there is strong agreement between the data for the predictions and the outcome. The small deviations in the data sets may be related to local deformation effects, such as folding. Such effects are difficult to interpret from drillhole data (due to the small diameter of the drill core), and are also probably filtered from the tunnel data, as the foliation measured on the tunnel wall refers to the general or mean orientation of the foliation in a specific tunnel section.

- The predictions seem to give a reasonable idea of the general frequency of deformation zones within each predicted tunnel section, as the number of zone intersections in each prediction is similar to their number in the outcome. However, the current models mainly describe site-scale major structures, whereas more local, smaller-scale features are mapped in the tunnel. This difference in resolution explains some of the discrepancies between the predicted and observed deformation zone intersections.

- Major differences exist between the fracture data from the pilot holes and the data collected from the tunnel walls, see e.g. Figure 11-19, with the difference being most pronounced in the data on fracture frequency – the frequencies in the tunnel data are more than 50% less than those of the pilot hole data. There could be several reasons for such discrepancies, but two levels of incoherence can be found in general between the pilot hole and mapped tunnel fracture data: (1) fracture attributes may be mapped differently in the core and on the tunnel wall - this depends on the conditions under which the mapping is taking place, the different mapping scales and possibly also on the variable opinions of the geologists who carry out the mapping; and (2) unavoidable differences, such as large number of single mineral fillings in pilot hole data and biases in the orientation distribution depending on the geometry of the mapped subjects and biases caused by the different sizes of the sampling volumes.
11.2.2 Rock Mechanics – ability to predict rock stability

The rock mechanics prediction-outcome work, see Section 9.3, has been concentrated on predicting the level of rock spalling in the ONKALO and a comparison with the observations. The predictions involve a knowledge of the rock stress and the rock strength and will vary according to the orientation of the ONKALO tunnel sections and their depth.

Spalling predictions for the ONKALO ramp at depths from 195 to 296 m (chainage interval 2080 – 3135 m) indicate where there is a 1% or a 10% probability of spalling, with the highest probability when the ONKALO ramp is orientated NE-SW, i.e. sub-perpendicular to the direction of the maximum in situ horizontal stress. The percentage probability of failure incorporates both the probability of failure itself, plus the amount of spalling that is expected to be experienced at a particular location. As can be seen in Figure 11-20, the observed rock damage accords quite well with the prediction, because almost all of the damage is in the NE-SW trending tunnel sections or in a region where the stress has been concentrated by adjacent excavation.

These studies will become increasingly important as the ONKALO reaches greater depths and the stress levels and probability of spalling increases. Section 9.3 also presents a prediction for the next tunnel loop (chainages 3117-4340 m), assuming different in situ stress orientations, and this prediction will be assessed in the next Site Report.
11.2.3 Hydrogeological impacts

Predicting inflow to the ONKALO and the resulting hydrogeological and chemical impacts

The open tunnel system may affect the groundwater flow regime at the site for hundreds of years. The inflow of groundwater into the open tunnel system may result in drawdown of the groundwater table, intrusion of surface water containing oxygen and carbon dioxide deep into the bedrock and upconing of deep saline groundwater. An assessment and predictions of these impacts, using the site-scale flow model, have been presented in previous Site Reports and have now been updated.

When modelling tunnel inflow, changes to the hydraulic properties of the rock close to the excavations need to be taken into account. Grouting, which is being applied during the excavation to limit the inflow to the ONKALO (and will also be used during the excavation and operational phase of the future repository), reduces the conductivity of the hydrogeological zones (HZ) and sparsely-fractured rock in the vicinity of the tunnels. Grouting has been used within the HZs and, at shallow depths, and also in the rock outside these zones. At greater depths in the sparsely-fractured rock, grouting has

Figure 11-20. Predicted locations where the highest probability of spalling occurs (1% and 10%) in the ONKALO ramp (third loop) are highlighted by different colours and observed rock falls marked by stars.
proved to be unnecessary, so far, mainly because the rock contains very few transmissive fractures, but also because the permeability of rock tends to decrease transverse to the tunnels, due to mechanical coupling, leading to a decrease in fracture apertures (what is referred to as positive skin). In the flow model, this is described by locally decreasing the conductivity and transmissivity in the vicinity of the tunnels, and by calibrating the calculated inflow against the observed total inflow into the tunnel.

SR2006 (Andersson et al. 2007) presented inflow and drawdown predictions using the 2006 flow model, locally calibrated to four measurements at tunnel chainage 580 m and two measurements at chainage 990 m. However, the results of the monitoring programme now show that the 2006 flow model clearly overestimated the hydraulic impact of the ONKALO. Significantly more information on the inflow (about 150 observations) was available for this recent modelling update (Vaittinen et al. 2008b) and, after calibration of the hydraulic properties around the tunnels, the current flow model was able to capture the observations very well.

The monitored impact of the ONKALO on the water table, as measured in shallow holes, has been minimal so far; however, its impact on the hydraulic head in deep, packed-off sections in some drillholes located close to the ONKALO is greater. Because the inflow is the main source of disturbances, the 2006 flow model overestimated the impact of the ONKALO, both in terms of the hydraulic heads in the shallow observation holes and also in the deep packed-off drillholes. In contrast, a good match between the calculated and observed hydraulic heads was obtained using the current flow model, as shown in Figure 11-21.

The calibrated flow model has also been used to predict changes in groundwater composition. The calculations showed that because the open tunnels draw groundwater from all directions in the bedrock, this is likely to cause an increase in the mixing of water types. Following the advance of the excavations, the tunnels draw increasingly fresh water from the surface, thereby diluting the groundwater at greater and greater depths. Simultaneously, the model shows the salinity of the groundwater gradually starting to rise around and below the tunnel system. Whereas the 2006 flow model predicted only a moderate upconing at the lower characterisation level by the year 2015, the current flow model shows an increase in the maximum TDS from about 21 g/L (initial value) up to 30 g/L. However, due to a lack of representative monitoring of TDS values and, especially, a lack of time series salinity data, it is currently difficult to judge the validity of the salinity model in the presence of the tunnels.
Figure 11-21. Observed and simulated hydraulic heads in selected packed-off sections of the drillholes. The times, at which the tunnels intersect the HZs passing through the drillhole sections or the rock near the sections, are denoted by the dashed lines (compiled from Figures 9-43 and 9-44).

Prediction of water-conducting fractures in tunnel pilot holes PH8 and PH9

The predictive capability of the Hydro-DFN model is tested by predicting the frequency and magnitudes of water-conducting fractures in two sub-horizontal pilot drillholes, PH8 and PH9, see Section 9.4. The adequacy of these predictions will be considered in the next update of the Hydro-DFN model (and reported in the next Site Report), when these pilot holes have been drilled and their data examined.

11.3 Confidence and unresolved issues

As concluded in Chapter 10, there is a high level of confidence in key aspects of the current Olkiluoto site descriptive model. The main reason for this confidence is the relative wealth of data from the central part of the Island and the consistency between independent data from different disciplines. There is, however, less confidence in some aspects of the model. This lack of confidence is handled by providing wide uncertainty ranges and bounding estimates, or by the development of alternative models. Most, but not all, of the low confidence aspects are judged to be of relatively limited importance for long-term safety.

The key remaining issues concern:

- Characterising the eastern part of the Island, such that the level of understanding will be comparable with that of the central part.
- Further advancing the rock stress and rock strength regime for stability estimations at relevant repository depths.
- Further advancing the hydrogeochemical understanding of processes of importance for long-term safety, e.g. processes affecting the sulphide content, the origin of methane, the distribution of groundwaters at the detailed scale and the relationship between groundwaters and pore waters.
• Further advancing the understanding of detailed-scale migration properties, including site-specific data on matrix properties.

• Further focusing on the ability to forecast and describe conditions of importance for long-term safety at the tunnel scale, i.e. as support to the RSC programme.
12 CONCLUDING REMARKS

This chapter concludes Site Report 2008 (referred to throughout the report as SR2008), by listing its overall achievements and discussing issues to be considered for further site characterisation and modelling.

12.1 Overall achievements and fulfilment of objectives

This third version of the Olkiluoto Site Report updates the Olkiluoto Site Report 2006 (Andersson et al. 2007) with the data and knowledge obtained up to December 2007. It has been confirmed that the report provides the expected input to the preliminary versions of the Safety Case. It assesses the disturbances caused by the construction of the ONKALO and, by making use of repeated Prediction/Outcome studies, it assess how the increased level of knowledge and the experience gained from the construction of the ONKALO has enhanced the level of site understanding and Posiva’s predictive capability. The report also assesses the uncertainty and confidence in the description and addresses developments and advances made, specifically in relation to the main issues identified in Site Report 2006, with a focus on those issues judged to be most important for the safety case. The report thus meets the objectives stated in Chapter 1.

The main product of the modelling has been to develop a descriptive model of the site, i.e. a model describing the geometry and properties of the bedrock and the surface and groundwater systems, and also the associated interacting processes and mechanisms. This model is distinct from the measured data themselves. Modelling involves interpreting data, interpolating or extrapolating between and away from measurement points and calibrating the model against data, based on various assumptions regarding the conceptual model employed. For practical reasons, the Site Descriptive Model is divided into separate components for the surface system, geology, rock mechanics, hydrogeology, hydrogeochemistry and transport, and these are presented in individual chapters. The main advances since Site Report 2006 are:

- The modelled area has been expanded to cover the eastern part of Olkiluoto Island in more detail, although the data density, especially in terms of deep drillholes, is still quite limited in the east.

- The geological model has been revised according to new data and interpretations. This has improved the consistency between the locations of the deformation zones in the geological model and the hydraulic zones in the hydrogeological model.

- New 3D seismic data have been incorporated within the geological model and an initial model for the eastern part of the Island is presented. Site-scale brittle deformation zones are extrapolated to intersect the surrounding regional lineaments, unless prohibited by direct observations to the contrary. The alteration model has been revised, showing a clear correspondence between the illitisation and the site-scale fault zones.

- A first account of the development of the brittle deformation history of the site is provided.

- A new geological DFN model has been developed, that considering mapped fracture traces from both the surface and the ONKALO.
A new stress state model and fracture and fracture zone properties are presented. More rock mechanics data (e.g. rock response data) from the ONKALO are available.

A new hydrogeological DFN model has been developed.

An updated site scale (EPM) flow model has been developed.

There has been an improvement in the understanding of the groundwater composition under low transmissive conditions. The importance of organics in controlling the groundwater composition of recently-infiltrated groundwaters has been clarified, due to the availability of many more isotopic and microbial data.

Transport properties are included in the report.

In other aspects of the Site Report, the 2008 model version is more a refinement of the 2006 model. Generally, there have been few surprises in the data obtained from the ONKALO and the Olkiluoto characterisation programmes, and the revisions to the model are concerned with details.

### 12.2 Issues to be considered for further site characterisation and modelling

As concluded in Chapter 10, and restated in Section 11.3, there is a high level of confidence in key aspects of the current Olkiluoto site descriptive model. There is less confidence in some aspects of the model and 26 critical issues have been identified, however, this lack of confidence can be handled, to a considerable extent, by providing wide uncertainty ranges and bounding estimates, or by the development of alternative models. The lack of confidence in these specific areas does not necessarily, therefore, warrant further characterisation and modelling. Some issues are, however, more significant, including:

- Characterising the eastern part of the island, such that the level of understanding becomes comparable with that of the central part of the island, i.e. what is referred to as the Well Characterised Area (WCA).

- Further advancing the rock stress and rock strength regime to allow reliable stability estimates to be made at relevant repository depths.

- Further advancing the hydrogeochemical understanding of processes of importance for long-term safety, e.g. processes affecting the sulphide content, the origin of methane, the distribution of groundwaters at the detailed scale and the relationship between groundwaters and pore waters.

- Further advancing the understanding of detailed-scale migration properties, including site-specific data on the matrix properties.

- Further focusing on the ability to forecast and describe conditions of importance for long-term safety at the tunnel scale, i.e. as support to the current RSC programme.

These issues will be addressed in Posiva’s further characterisation and modelling work.
APPENDICES
Appendix 2-1. List of geological investigations carried out at Olkiluoto. References to reports containing data collected since Site Description 2006 (Andersson et al. 2007) are shown in bold.

<table>
<thead>
<tr>
<th>Investigations</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface investigations</strong></td>
<td></td>
</tr>
<tr>
<td>Geology and hydrogeology on the Ulkopää site</td>
<td>Åikäs (1986)</td>
</tr>
<tr>
<td>Petrographic and mineralogical study at the Ulkopää site</td>
<td>Lindberg (1986)</td>
</tr>
<tr>
<td>Bedrock and fracture mapping</td>
<td>Paulamäki (1989)</td>
</tr>
<tr>
<td>Mapping of ductile structures</td>
<td>Paulamäki &amp; Koistinen (1991)</td>
</tr>
<tr>
<td>Fracture mapping above the VLJ repository</td>
<td>Sacklén (1994)</td>
</tr>
<tr>
<td>Geological mapping of two sludge basins</td>
<td>Åikäs (1995)</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK1,2</td>
<td>Paulamäki (1995)</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK2,2</td>
<td>Paulamäki (1996)</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK4,2</td>
<td>Paulamäki (2004a)</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK7,2</td>
<td>Paulamäki (2004b)</td>
</tr>
<tr>
<td>Dating of the diabase dyke from investigation trench TK3,2</td>
<td>Mänttäri et al. (2004)</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK11, the storage hall area</td>
<td>Mattila et al. (2006)</td>
</tr>
<tr>
<td>Geological mapping of the Olkiluoto 3 construction site 1,2</td>
<td>Talikka (2005) (WR 2005-32)</td>
</tr>
<tr>
<td>Geological mapping of the ONKALO open cut 1,2</td>
<td>Talikka (2005) (WR 2005-33)</td>
</tr>
<tr>
<td>Geological mapping of the investigation trench OL-TK8 at the Olkiluoto study site 1,2</td>
<td>Engström (2005) (WR 2005-44)</td>
</tr>
<tr>
<td>Geological mapping of the investigation trench OL-TK9 at the Olkiluoto study site 1,2</td>
<td>Nordbäck &amp; Talikka (2006) (WR 2006-51)</td>
</tr>
<tr>
<td>Studies of Quaternary Deposits of Investigation Trench OL-TK13 at the Olkiluoto Study Site, Eurajoki, SW Finland</td>
<td>Huhtala (2007) (WR 2007-34)</td>
</tr>
<tr>
<td>Ground Penetrating Radar investigations in ONKALO Tunnel and Eastern part of the Olkiluoto Investigation Area</td>
<td>Sipola (2007) (WR 2007-12)</td>
</tr>
<tr>
<td>Preliminary Paleomagnetic Study on Different Rock Types in Olkiluoto Area</td>
<td>Mertanen (2007) (WR 2007-22)</td>
</tr>
<tr>
<td>Illite K-Ar Dating of Fault Breccia Samples from ONKALO Underground Research, Olkiluoto, Eurajoki, SW Finland</td>
<td>Mänttäri et al. (2007) (WR 2007-67)</td>
</tr>
<tr>
<td><strong>Subsurface mapping</strong></td>
<td></td>
</tr>
<tr>
<td>---------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------</td>
</tr>
<tr>
<td>Engineering geological mapping of the access tunnel of the VLJ repository</td>
<td>Ikävalko &amp; Niskanen (1989)</td>
</tr>
<tr>
<td>Geological mapping of the VLJ repository</td>
<td>Ikävalko &amp; Äikäs (1991)</td>
</tr>
<tr>
<td>Fracture mapping of the research tunnel in the VLJ repository</td>
<td>Äikäs &amp; Sacklén (1993)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Core drilling</strong></td>
<td></td>
</tr>
<tr>
<td>Shallow drillings by IVO</td>
<td></td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR1&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Imatran Voima Oy (1974), Jokinen (1990)</td>
</tr>
<tr>
<td>Shallow boreholes, PP1-PP36&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Suomen Malmi (1989a)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR2&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Suomen Malmi (1989b)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR3&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Suomen Malmi (1989c), Rautio (1995c)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR4&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Suomen Malmi (1989d)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR5&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Suomen Malmi (1990a), Rautio (1995b)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR6&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Suomen Malmi (1990b)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR7&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Rautio &amp; With (1990), Rautio (2000b)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR8&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Jokinen (1994), Rautio (2000a)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR9&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Rautio (1995a), Niinimäki (2002g)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR10&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Rautio (1996b)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR11&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Rautio (1996a)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR12&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Rautio (1999)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR13&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2000)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR14&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2001a)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR15&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2001b)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR16&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2002a)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR17&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2002b)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR18&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2002c)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR19&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2002d)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR20&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2002e)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR21&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2002f)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR22&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2002h)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR23&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2002i), Niinimäki (2004b)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR24&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2002j)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR25&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2003a)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR26&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2003b)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR27&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2003c)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR28&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2003d)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR29&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2003e)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR30&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2004)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR31&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2005a)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR32&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2005b)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR33&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>Niinimäki (2005c)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR34</td>
<td>Niinimäki (2005d)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR35</td>
<td>Niinimäki (2005a)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR36</td>
<td>Niinimäki (2005b)</td>
</tr>
<tr>
<td>Drilling of deep borehole OL-KR37</td>
<td>Niinimäki (2005b)</td>
</tr>
</tbody>
</table>
Drilling of deep borehole OL-KR38
Drilling of deep borehole OL-KR39
Drilling of deep borehole OL-KR40 at Olkiluoto in Eurajoki 2005-2006
Drilling of deep borehole OL-KR41 at Olkiluoto in Eurajoki 2006
Drilling of deep borehole OL-KR42 at Olkiluoto in Eurajoki 2006
Drilling of deep borehole OL-KR43 at Olkiluoto in Eurajoki 2006
Drilling of deep borehole OL-KR44 at Olkiluoto in Eurajoki 2007
Drilling of deep borehole OL-KR45 at Olkiluoto in Eurajoki 2007
Drilling of deep borehole OL-KR46 at Olkiluoto in Eurajoki 2007
Drilling of deep borehole OL-KR47 at Olkiluoto in Eurajoki 2007-2008
Drilling of deep borehole OL-KR48 at Olkiluoto in Eurajoki 2007
Drilling of deep borehole OL-KR49
Drilling of deep borehole OL-KR50
Core Drilling of Short Drillholes at Olkiluoto in Eurajoki 2006
Drilling and the Associated borehole Measurements of the Pilot hole ONK-PH3
Drilling and the Associated borehole Measurement of the Pilot hole ONK-PH4
Drilling and the Associated borehole Measurement of the Pilot hole ONK-PH5
Drilling and the Associated Drillhole Measurements of the Pilot hole ONK-PH6
Drilling and the Associated Drillhole Measurements of the Pilot Hole ONK-PH7
Core Drilling of Borehole ONK-PVA4 in ONKALO at Olkiluoto 2007
Core Drilling of Drillholes ONK-PP115-ONK-PP120 in ONKALO at Olkiluoto 2007
Core Drilling of Drillholes ONK-PP115, ONK-PP165 and ONK-PP167 in ONKALO at Olkiluoto 2008
Injektointi- ja kontrollireikien kairaus ja vesimeneekkimittaus poisto- ja ilmanvaihtokuulule Olkiluodossa vuosina 2006-2007
Extension Core Drilling of Deep Borehole OL- KR31 at Olkiluoto in Eurajoki 2006

**Drillhole investigations**

Petrography, litho geochemistry and petrophysics, borehole KR1-KR5
Petrography, litho geochemistry and petrophysics, borehole KR6
Dating of fracture minerals, borehole KR1

Lindberg & Paananen (1991a)
Lindberg & Paananen (1992)
Blomqvist et al. (1992)

Not reported yet
Not reported yet

Rautio (2005e) (WR 2005-58)
Niinimäki (2005c) (WR 2005-68)
Öhberg et al. (2006) (WR 2006-20)
Öhberg et al. (2006) (WR 2006-71)
Öhberg et al. (2006) (WR 2006-72)
Öhberg et al. (2007) (WR 2007-68)
Öhberg et al. (2008) (WR 2007-97)
Rautio (2007) (TR 2007-41)
Rautio (2008) (TR 2008-08)
Petrology and low temperature fracture minerals, boreholes KR2-KR8 and KR10
Petrology and low temperature fracture minerals, borehole KR9
Isotopic and fluid inclusion study of fracture calcite, borehole KR1
Petrology and low temperature fracture minerals, borehole KR11
C, O and Sr isotopic characteristics of fracture calcites
Foliation: Geological background, rock mechanics significance and preliminary investigations at Olkiluoto
U-Pb ages for tonalitic gneiss, pegmatitic granite and diabase dyke, Olkiluoto study site Eurajoki, SW Finland
Statistical model of fractures based on data from OL-TK7, OL-TK11, OL-KR24, OL-PH1 and ONKALO PL 0-140 m
Petrology, Petrophysics and Fracture Mineralogy of the Drill Core Sample OL-KR8
Petrology, Petrophysics and Fracture Mineralogy of the Drill Core Sample OL-KR15
Petrology, Petrophysics and Fracture Mineralogy of the Drill Core Sample OL-KR21
U-Pb Ages for two Tonalitic Gneisses, Pegmatitic Granites and K-feldspar Porphyries, Olkiluoto Study Site, Eurajoki SW Finland
Hydrothermal alteration at Olkiluoto: Mapping of drill core samples

Summary reports

Geology and hydrology of the Ulkopää Cape at Olkiluoto
Geology of the Olkiluoto area
Geological and geophysical investigations at the Olkiluoto site
Olkiluoto site report
Bedrock of southern Satakunta
Baseline conditions at Olkiluoto
Petrology of Olkiluoto
Revision of the lineament interpretations of the Olkiluoto area in the light of acoustic-seismic data from adjacent marine areas
Lineament interpretation of the Olkiluoto area
Geological model of ONKALO area
ONKALO Area Model - version 1
Geological Model of the Olkiluoto site area
Geological Model of the Olkiluoto Site - Version 1.0
Understanding brittle deformation at the Olkiluoto site. A Preliminary Survey of Background Knowledge for site characterisation and geological modeling

Gehör et al. (1996)
Gehör et al. (1997)
Blyth et al. (1998)
Gehör et al. (2000)
Karhu (2000)
Gehör et al. (2001)
Milnes et al. (2006) (WR 2006-03)
Mänttäri et al. (2006) (WR 2006-12)
Tuominen et al. (2006) (WR 2006-22)
Gehör et al. (2007) (WR 2007-42)
Gehör et al. (2007) (WR 2007-43)
Gehör et al. (2007) (WR 2007-44)
Gehör et al. (2007) (WR 2007-45)
Gehör et al. (2007) (WR 2007-47)
Gehör et al. (2007) (WR 2007-48)
Mänttäri et al. (2007) (WR 2007-70)
Ahokas & Äikäs (1991)
Anttila et al. (1992)
Anttila & Heikkinen (1996)
Anttila et al. (1999)
Paulamäki et al. (2002)
Posiva (2003)
Korhonen et al. (2005) (WR 2005-34)
Paananen et al. (WR 2006-13)
Paananen et al. (2008) (WR 2007-71)
GeoMTF 2006 (WR 2006-37)
<table>
<thead>
<tr>
<th>Title</th>
<th>Authors and Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depositional history and tectonic regimens within and in the margins of the Fennoscandian Shield during the last 1300 million years</td>
<td>Paulamäki &amp; Paananen 2006 (WR 2006-43)</td>
</tr>
<tr>
<td>Regional Lineament Analysis of the Southern Satakunta Area</td>
<td>Paananen &amp; Kuivamäki (2007) (WR 2007-04)</td>
</tr>
</tbody>
</table>
**Appendix 2-2.** List of geophysical investigations carried out at Olkiluoto. References to reports containing data collected since Site Description 2006 (Posiva 2007) are shown in bold.

<table>
<thead>
<tr>
<th>Geophysical data</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground surveys</td>
<td>Taanila 1975</td>
</tr>
<tr>
<td></td>
<td>Taanila &amp; Hytti 1978</td>
</tr>
<tr>
<td></td>
<td>Laurila 1989 (WR 89-35)</td>
</tr>
<tr>
<td></td>
<td>Paananen et al. 1991 (WR 91-28)</td>
</tr>
<tr>
<td></td>
<td>Jokinen &amp; Jokinen 1994 (PATU WR 94-44)</td>
</tr>
<tr>
<td></td>
<td>Elo 2001 (WR 2001-05)</td>
</tr>
<tr>
<td></td>
<td>Leino 2001 (WR 2001-27)</td>
</tr>
<tr>
<td></td>
<td>Ihalainen &amp; Lahti 2002 (WR 2002-24)</td>
</tr>
<tr>
<td></td>
<td>Lahti 2002 (WR 2002-51)</td>
</tr>
<tr>
<td></td>
<td>Sutinen 2002 (WR 2002-52)</td>
</tr>
<tr>
<td></td>
<td>Ihalainen 2003 (WR 2003-12)</td>
</tr>
<tr>
<td></td>
<td>Lahti &amp; Tammenmaa (WR 2003-23)</td>
</tr>
<tr>
<td></td>
<td>Ahokas 2003 (WR 2003-24)</td>
</tr>
<tr>
<td></td>
<td>Lehtimäki 2003 (WR 2003-62)</td>
</tr>
<tr>
<td></td>
<td>Lehtimäki 2003 (WR 2003-63)</td>
</tr>
<tr>
<td></td>
<td>Sutinen 2003 (WR 2003-75)</td>
</tr>
<tr>
<td></td>
<td>Cosma et al. 2003 (POSIVA-2003-01)</td>
</tr>
<tr>
<td></td>
<td>Heikkinnen et al. 2004 (WR 2004-16)</td>
</tr>
<tr>
<td></td>
<td>Lahti 2004 (WR 2004-29)</td>
</tr>
<tr>
<td></td>
<td>Jokinen &amp; Lehtimäki 2004 (WR 2004-38)</td>
</tr>
<tr>
<td></td>
<td>Ihalainen 2005 (WR 2005-15)</td>
</tr>
<tr>
<td></td>
<td>Lehtimäki &amp; Jokinen 2005 (WR 2005-43)</td>
</tr>
<tr>
<td></td>
<td>Jokinen &amp; Lehtimäki 2006 (WR 2006-69)</td>
</tr>
<tr>
<td></td>
<td>Julkunen &amp; Gebühr 2007 (WR 2007-64)</td>
</tr>
<tr>
<td></td>
<td>Jokinen &amp; Lehtimäki 2008 (WR 2007-79)</td>
</tr>
<tr>
<td></td>
<td>Korhonen &amp; Lehtimäki 2008 (WR 2007-80)</td>
</tr>
<tr>
<td></td>
<td>Tarvainen &amp; Lahti 2008 (WR 2008-02)</td>
</tr>
<tr>
<td>Drillhole geophysics</td>
<td>Front et al. 1990 (WR 90-08)</td>
</tr>
<tr>
<td></td>
<td>Front et al. 1990 (WR 90-47)</td>
</tr>
<tr>
<td></td>
<td>Carlsten 1996 (WR 96-03e)</td>
</tr>
<tr>
<td></td>
<td>Front et al. 1996 (PATU WR 96-08)</td>
</tr>
<tr>
<td></td>
<td>Laurila &amp; Tammenmaa 1996 (WR 96-14)</td>
</tr>
<tr>
<td></td>
<td>Lowit et al. 1996 (WR 96-33e)</td>
</tr>
<tr>
<td></td>
<td>Hassinen et al. 1996 (WR 96-41)</td>
</tr>
<tr>
<td></td>
<td>Carlsten 1996 (WR 96-54e)</td>
</tr>
<tr>
<td></td>
<td>Strähle 1996 (WR 96-59e)</td>
</tr>
<tr>
<td></td>
<td>Siddans &amp; Wild 1996 (WR 96-66e)</td>
</tr>
<tr>
<td></td>
<td>Front et al. 1997 (WR 97-17)</td>
</tr>
<tr>
<td></td>
<td>Ikävalko 1998 (WR 98-04)</td>
</tr>
<tr>
<td></td>
<td>Heikkinen et al. 1999 (WR 99-61)</td>
</tr>
<tr>
<td></td>
<td>Julkunen et al. 2000 (WR 2000-02)</td>
</tr>
<tr>
<td></td>
<td>Front et al. 2000 (WR 2000-37)</td>
</tr>
<tr>
<td></td>
<td>Okko et al. 2000 (WR 2000-39)</td>
</tr>
<tr>
<td></td>
<td>Front et al. 2001 (WR 2001-02)</td>
</tr>
<tr>
<td></td>
<td>Front et al. 2001 (WR 2001-03)</td>
</tr>
<tr>
<td></td>
<td>Hassinen et al. 2001 (WR 2001-30)</td>
</tr>
<tr>
<td></td>
<td>Heikkinen et al. 2001 (WR 2001-35)</td>
</tr>
<tr>
<td></td>
<td>Kennaugh et al. 2002 (WR 2002-02)</td>
</tr>
<tr>
<td></td>
<td>Wild et al. 2002 (WR 2002-11)</td>
</tr>
<tr>
<td>Category</td>
<td>Authors</td>
</tr>
<tr>
<td>---------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Julkunen et al. 2002</td>
<td>(WR 2002-32)</td>
</tr>
<tr>
<td>Hassinen et al. 2003</td>
<td>(WR 2003-05)</td>
</tr>
<tr>
<td>Julkunen et al. 2003</td>
<td>(WR 2003-10)</td>
</tr>
<tr>
<td>Julkunen et al. 2003</td>
<td>(WR 2003-50)</td>
</tr>
<tr>
<td>Julkunen et al. 2004</td>
<td>(WR 2004-11)</td>
</tr>
<tr>
<td>Julkunen et al. 2004</td>
<td>(WR 2004-17)</td>
</tr>
<tr>
<td>Julkunen et al. 2004</td>
<td>(WR 2004-18)</td>
</tr>
<tr>
<td>Lahti 2004</td>
<td>(WR 2004-27)</td>
</tr>
<tr>
<td>Lahti 2004</td>
<td>(WR 2004-28)</td>
</tr>
<tr>
<td>Lahti &amp; Heikkinen 2004</td>
<td>(WR 2004-43)</td>
</tr>
<tr>
<td>Heikkinen et al. 2004</td>
<td>(WR 2004-60)</td>
</tr>
<tr>
<td>Heikkinen et al. 2004</td>
<td>(WR 2004-62 Vol.1 and 2)</td>
</tr>
<tr>
<td>Lahti &amp; Heikkinen 2005</td>
<td>(WR 2005-04)</td>
</tr>
<tr>
<td>Lahti 2005</td>
<td>(WR 2005-06)</td>
</tr>
<tr>
<td>Lahti &amp; Heikkinen 2005</td>
<td>(WR 2005-17)</td>
</tr>
<tr>
<td>Majapuro 2005</td>
<td>(WR 2005-50)</td>
</tr>
<tr>
<td>Heikkinen et al. 2005</td>
<td>(WR 2005-60)</td>
</tr>
<tr>
<td>Kallio &amp; Julkunen 2005</td>
<td>(WR 2005-69)</td>
</tr>
<tr>
<td>Majapuro 2005</td>
<td>(WR 2005-73)</td>
</tr>
<tr>
<td>Kallio &amp; Julkunen 2005</td>
<td>(WR 2005-74)</td>
</tr>
<tr>
<td>Majapuro 2006</td>
<td>(WR 2006-07)</td>
</tr>
<tr>
<td>Majapuro 2006</td>
<td>(WR 2006-17)</td>
</tr>
<tr>
<td>Majapuro 2006</td>
<td>(WR 2006-26)</td>
</tr>
<tr>
<td>Majapuro 2006</td>
<td>(WR 2006-30)</td>
</tr>
<tr>
<td>Tarvainen 2007</td>
<td>(WR 2006-38)</td>
</tr>
<tr>
<td>Tarvainen 2006</td>
<td>(WR 2006-75)</td>
</tr>
<tr>
<td>Tarvainen 2007</td>
<td>(WR 2007-06)</td>
</tr>
<tr>
<td>Kuusisto 2007</td>
<td>(WR 2007-07)</td>
</tr>
<tr>
<td>Tarvainen 2007</td>
<td>(WR 2007-13)</td>
</tr>
<tr>
<td>Tarvainen 2007</td>
<td>(WR 2007-14)</td>
</tr>
<tr>
<td>Kallio &amp; Julkunen 2007</td>
<td>(WR 2007-58)</td>
</tr>
</tbody>
</table>

| VSP (+HSP, etc.)          | Cosma et al. 1996 (WR 96-11e)    | 1,2                              |
|                          | Cosma et al. 1996 (WR 96-60e)    | 1,2                              |
|                          | Rantataro 2001 (WR 2001-11)      |                                  |
|                          | Kuivamäki 2002 (WR 2002-xx)      |                                  |
|                          | Rantataro 2002 (WR 2002-38)      |                                  |
|                          | Balu et al. 2003 (WR 2003-13)    | 1,2                              |
|                          | Balu et al. 2004 (WR 2004-62 Vol.1) | 1,2 |
|                          | Heikkinen et al. 2004 (WR 2004-62 Vol.2) | 1,2 |
|                          | Enescu et al. 2007 (WR 2007-72)  |                                  |

| Mise-a-la-masse           | Paananen 1996 (WR 96-13)         | 1,2                              |
|                          | Lahti & Laurila 2003 (WR 2003-25) | 1,2                              |
|                          | Heikkinen & Lehtonen 2004 (WR 2004-51) | 1,2 |
|                          | Lehtonen 2006 (WR 2006-08)       | 1,2                              |
|                          | Lehtonen 2006 (WR 2006-48)      | 1,2                              |
|                          | Lehtonen & Tarvainen 2006 (WR 2006-86) |      |
|                          | Lehtonen & Mattila 2007 (WR 2007-02) |      |
|                          | Tarvainen 2007 (WR 2007-06)     |                                  |
|                          | Lehtonen 2008 (WR 2007-100)     |                                  |
|                          | Tarvainen 2008 (WR 2008-30)     |                                  |

<p>| Summary geophysics       | Ahokas et al. 1992 (YJT-92-34) |                                  |
|                          | Heikkinen et al. 1996 (WR PATU-96-84) |      |
|                          | Anttila &amp; Heikkinen 1996 (WR PATU-96-89) |      |</p>
<table>
<thead>
<tr>
<th>Thermal studies</th>
<th>Kukkonen &amp; Lindberg 1995 (YJT-95-08)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kukkonen &amp; Lindberg 1998 (WR 98-09e)</td>
</tr>
<tr>
<td></td>
<td>Kukkonen et al. 2000 (WR 2000-25)</td>
</tr>
<tr>
<td></td>
<td>Kukkonen 2000 (WR 2000-40)</td>
</tr>
<tr>
<td></td>
<td>Kukkonen et al. 2001 (WR 2001-23)</td>
</tr>
<tr>
<td></td>
<td>Kukkonen et al. 2004 (WR 2004-20)</td>
</tr>
<tr>
<td>Other</td>
<td>Heikkinen et al 1996 (WR PATU-96-09)</td>
</tr>
<tr>
<td></td>
<td>Ikonen 1996 (WR 96-45e)</td>
</tr>
<tr>
<td></td>
<td>Öhberg 1996 (WR 96-94)</td>
</tr>
<tr>
<td></td>
<td>Anttila et al. 1999 (POSIVA-99-10)</td>
</tr>
<tr>
<td></td>
<td>Ahokas et al. 2000 (WR 2000-26)</td>
</tr>
<tr>
<td></td>
<td>Paananen 2004 (WR 2004-01)</td>
</tr>
<tr>
<td></td>
<td>Nummela 2004 (WR 2004-22)</td>
</tr>
<tr>
<td></td>
<td>Öhman, Heikkinen &amp; Lehtimäki 2007 (WR 2006-114)</td>
</tr>
<tr>
<td></td>
<td>Saksa, Lehtimäki &amp; Heikkinen 2007 (WR 2007-10)</td>
</tr>
<tr>
<td></td>
<td>Paananen, Lehtonen &amp; Korhonen 2007 (WR 2007-49)</td>
</tr>
<tr>
<td></td>
<td>Cosma &amp; Juhlin 2007 (WR 2007-65)</td>
</tr>
<tr>
<td></td>
<td>Cosma et al. 2008 (WR 2008-43)</td>
</tr>
<tr>
<td></td>
<td>Öhman, Heikkinen &amp; Lehtimäki 2008 (WR 2008-18)</td>
</tr>
</tbody>
</table>
### Appendix 2-3. The list of hydrogeological investigations carried out at Olkiluoto. References to reports published since Site Description 2006 (Posiva 2007) is shown in bold in the list.

<table>
<thead>
<tr>
<th>Investigation or analysis</th>
<th>Area or drillhole</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Results of Monitoring at Olkiluoto in 2006: Hydrology</td>
<td>Installation of multi packer Equipment into Drillholes at Olkiluoto Since 1999</td>
<td>Tammisto et al. (WR 2006-54) 1, 2</td>
</tr>
<tr>
<td>Groundwater table and hydrogeological conditions at Ulkopää cape 1985-1987</td>
<td>VLJ-repository site</td>
<td>Klockars et al. 2007 (WR 2007-50)</td>
</tr>
<tr>
<td>Long-term monitoring of precipitation, sea level, water-table and hydraulic head in open and packed-off drill holes</td>
<td>In total 40 observation holes In total 28 observation holes In total 33 observation holes In total 92 observation holes</td>
<td>Ahokas &amp; Herva 1993 1, 2, Hänninen 1996 1, 2, Lehtimäki 2001 1, 2, Voipio et al. 2003 1, 2</td>
</tr>
<tr>
<td>------</td>
<td>-------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OL-KR12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OL-KR13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OL-KR14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OL-KR15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OL-KR2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OL-KR16-OL-KR18 (including B-holes)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OL-KR4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and OL-KR31, in 2006</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measurement of hydraulic conductivity and transmissivity by DIFF-tool</th>
<th>Hämäläinen 1997a, b, c, d, e, 1998, 2003a,b,c, 2004a,b^{1,2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLPR0015-OLPR0980, ONK-KR1 -ONK-KR4, ONK-PVA1</td>
<td>Pöllänen &amp; Rouhiainen 2005a (WR 2005-51)^{1,2}</td>
</tr>
<tr>
<td></td>
<td>Pöllänen &amp; Rouhiainen 2005b (WR 2005-52)^{1,2}</td>
</tr>
<tr>
<td></td>
<td>Pöllänen et al. 2005 (WR 2005-47)^{1,2}</td>
</tr>
<tr>
<td></td>
<td>Pöllänen 2006 (WR 2006-47)^{1,2}</td>
</tr>
<tr>
<td></td>
<td>Väisäsvaara &amp; Pöllänen 2007 (WR 2007-16)</td>
</tr>
<tr>
<td></td>
<td>Väisäsvaara et al. 2008 (WR 2008-16)</td>
</tr>
<tr>
<td></td>
<td>Väisäsvaara &amp; Pöllänen 2007 (WR 2007-16)</td>
</tr>
<tr>
<td></td>
<td>Reiman et al. 2007 (WR 2006-65)</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Summary and modelling reports</td>
<td>Simulation of hydraulic disturbances caused by the Underground Rock Characterisation facility in Olkiluoto Simulation of hydraulic disturbances caused by the decay heat of the repository in Olkiluoto</td>
</tr>
<tr>
<td>Modelling of hydro zones for the layout planning and numerical flow model in 2006</td>
<td>Ahokas &amp; Vaittinen 2008 (WR 2007-01)</td>
</tr>
<tr>
<td>Surface and Near-Surface Hydrological Model of Olkiluoto Island</td>
<td>Karvonen 2008 (WR 2008-17)</td>
</tr>
<tr>
<td>Compilation and Analysis of Hydrogeological Responses to Field Activities in Olkiluoto</td>
<td>Ahokas et al. 2008 (WR 2008-03)</td>
</tr>
</tbody>
</table>
**Appendix 2-4.** The list of hydrogeochemical investigations carried out at Olkiluoto. References to reports published since Site Description 2006 (Posiva 2007) is shown in bold in the list.

![Table](image)

<table>
<thead>
<tr>
<th>Hydrogeochemical data</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation, surface water and Baltic seawater</td>
<td>Honkasalo 1995a (WR PATU-95-32)</td>
</tr>
<tr>
<td></td>
<td>Honkasalo 1995b (WR PATU-95-54, no data in OIVA)</td>
</tr>
<tr>
<td></td>
<td>Tuominen 1994 (WR PATU-94-35)</td>
</tr>
<tr>
<td></td>
<td>Tuominen 1995 (WR PATU-95-17, no data in OIVA)</td>
</tr>
<tr>
<td></td>
<td>Paaso 2003 (WR 2003-18)</td>
</tr>
<tr>
<td>Shallow drillholes and groundwater observation tubes in overburden</td>
<td>Kröger 2004 (WR 2004-44)</td>
</tr>
<tr>
<td></td>
<td>Backman et al. 2002 (WR 2002-41)</td>
</tr>
<tr>
<td></td>
<td>Hatanpää 2002 (WR 2002-20)</td>
</tr>
<tr>
<td></td>
<td>Hirvonen 2005 (WR 2005-57)</td>
</tr>
<tr>
<td></td>
<td>Honkasalo 1995c (WR PATU-95-66)</td>
</tr>
<tr>
<td></td>
<td>Tuominen 1998 (WR 98-07)</td>
</tr>
<tr>
<td></td>
<td><strong>Pedersen 2007 (WR 2007-20)</strong></td>
</tr>
<tr>
<td>Groundwater sampling in deep drillholes</td>
<td>Haveman, Pedersen &amp; Ruotsalainen 1998 (WR 98-09)</td>
</tr>
<tr>
<td></td>
<td>Haveman, Larsdotter, Nilsson &amp; Pedersen 2000 (WR 2000-06)</td>
</tr>
<tr>
<td></td>
<td>Helenius et al. 1998 (WR 98-23)</td>
</tr>
<tr>
<td></td>
<td>Hirvonen et al. 2004a (WR 2004-19)</td>
</tr>
<tr>
<td></td>
<td>Hirvonen et al. 2004b (WR 2004-34)</td>
</tr>
<tr>
<td></td>
<td>Hirvonen &amp; Hatanpää. 2005 (WR 2005-77)</td>
</tr>
<tr>
<td></td>
<td>Hirvonen &amp; Hatanpää 2005a (WR 2005-75)</td>
</tr>
<tr>
<td></td>
<td>Hirvonen &amp; Hatanpää 2005b (WR 2005-80)</td>
</tr>
<tr>
<td></td>
<td>Karitunen et al. 1999 (WR 99-70)</td>
</tr>
<tr>
<td></td>
<td>Karitunen et al. 2000a (WR 2000-47)</td>
</tr>
<tr>
<td></td>
<td>Karitunen &amp; Mäntynen 2001 (WR 2001-26)</td>
</tr>
<tr>
<td></td>
<td>Kröger et al. 2004 (WR 2004-68)</td>
</tr>
<tr>
<td></td>
<td>Kröger et al. 2003 (WR 2003-33)</td>
</tr>
<tr>
<td></td>
<td>Paaso et al. 2003a (WR 2003-20)</td>
</tr>
<tr>
<td></td>
<td>Paaso et al. 2003b (WR 2003-34)</td>
</tr>
<tr>
<td></td>
<td>Paaso &amp; Mäntynen 2002 (WR 2002-15)</td>
</tr>
<tr>
<td></td>
<td>Rantanen et al. 2002 (WR 2002-19)</td>
</tr>
<tr>
<td></td>
<td>Snellman 1996 (WR PATU-96-21)</td>
</tr>
<tr>
<td></td>
<td>Snellman et al. 1995a (WR PATU-95-57)</td>
</tr>
<tr>
<td></td>
<td>Snellman et al. 1995b (WR PATU-95-77)</td>
</tr>
<tr>
<td></td>
<td><strong>Lahdenperä 2006 (WR 2006-44)</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Hirvonen et al. 2007 (WR 2006-105)</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Hirvonen &amp; Hatanpää 2007 (WR 2006-51)</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Hirvonen, Hatanpää &amp; Ahokas 2007 (WR 2007-19)</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Lammimäki, Hatanpää, Ahokas &amp; Klockars 2008 (WR 2008-41)</strong></td>
</tr>
<tr>
<td>Groundwater sampling in ONKALO</td>
<td>Hatanpää &amp; Rantanen 2006 (WR 2006-36)</td>
</tr>
<tr>
<td></td>
<td>Lehtinen 2006 (WR 2006-28)</td>
</tr>
<tr>
<td></td>
<td>Lehtinen &amp; Hirvonen 2007 (WR 2006-28)</td>
</tr>
<tr>
<td></td>
<td>Manninen &amp; Mäkelä 2006 (WR 2006-42)</td>
</tr>
<tr>
<td></td>
<td>Mäkelä &amp; Manninen 2007 (WR 2007-23)</td>
</tr>
<tr>
<td></td>
<td>Takala &amp; Manninen 2007 (WR 2006-98)</td>
</tr>
<tr>
<td>In situ electrical conductivity (EC) measurements in deep drillholes</td>
<td>Pöllänen &amp; Rouhiainen 1996a (WR PATU-96-43e)</td>
</tr>
<tr>
<td></td>
<td>Pöllänen &amp; Rouhiainen 1996b (WR PATU-96-44e)</td>
</tr>
<tr>
<td></td>
<td>Pöllänen &amp; Rouhiainen 2000 (WR 2000-38)</td>
</tr>
<tr>
<td></td>
<td>Pöllänen &amp; Rouhiainen 2001 (WR 2000-51)</td>
</tr>
<tr>
<td></td>
<td>Pöllänen &amp; Rouhiainen 2002a (WR 2001-42)</td>
</tr>
<tr>
<td></td>
<td>Pöllänen &amp; Rouhiainen 2002c (WR 2000-29)</td>
</tr>
<tr>
<td>Monitoring results</td>
<td>Hirvonen, Lehtinen &amp; Hatanpää 2006 (WR 2006-67)</td>
</tr>
<tr>
<td>-------------------------------------------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Pitkänen et al. 2007 (WR 2007-51)</td>
</tr>
<tr>
<td></td>
<td>Pitkänen et al. 2008 (WR 2008-24)</td>
</tr>
<tr>
<td>Summary and modelling reports etc.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Anttila et al. 1999 (POSIVA-99-10)</td>
</tr>
<tr>
<td></td>
<td>Gascoyne 2000 (WR 2000-49)</td>
</tr>
<tr>
<td></td>
<td>Gascoyne 2005 (WR 2005-56)</td>
</tr>
<tr>
<td></td>
<td>Hatanpää et al. 2005 (WR2005-55)</td>
</tr>
<tr>
<td></td>
<td>Itävaara et al. 2005 (WR 2005-65)</td>
</tr>
<tr>
<td></td>
<td>Karttunen 2000 (WR 2000-34)</td>
</tr>
<tr>
<td></td>
<td>Karttunen et al. 2000b (WR 2000-50)</td>
</tr>
<tr>
<td></td>
<td>Lampén &amp; Snellman 1993 (YJT-93-14)</td>
</tr>
<tr>
<td></td>
<td>Luukkonen, Pitkänen &amp; Partamies 2003 (WR 2003-31)</td>
</tr>
<tr>
<td></td>
<td>Luukkonen, Pitkänen &amp; Partamies 2004 (WR 2004-08)</td>
</tr>
<tr>
<td></td>
<td>Luukkonen et al. 2005 (WR 2005-72)</td>
</tr>
<tr>
<td></td>
<td>Mäntynen 2005 (WR 2005-29)</td>
</tr>
<tr>
<td></td>
<td>Palmén &amp; Hellä 2003 (WR 2003-19)</td>
</tr>
<tr>
<td></td>
<td>Pedersen (2005) (WR 2006-09)</td>
</tr>
<tr>
<td></td>
<td>Pitkänen et al. 1996 (POSIVA-96-04)</td>
</tr>
<tr>
<td></td>
<td>Pitkänen et al. 1999a (POSIVA-98-10)</td>
</tr>
<tr>
<td></td>
<td>Pitkänen et al. 2004 (POSIVA-2003-07)</td>
</tr>
<tr>
<td></td>
<td>Pitkänen P. &amp; Partamies S. 2007 (POSIVA 2007-04)</td>
</tr>
<tr>
<td></td>
<td>Posiva Oy 2003 (POSIVA-2003-02)</td>
</tr>
<tr>
<td></td>
<td>Ruotsalainen &amp; Snellman 1996 (WR PATU-96-91E)</td>
</tr>
<tr>
<td></td>
<td>Snellman 1995 (WR PATU-95-18)</td>
</tr>
<tr>
<td></td>
<td>Hellä et al. 2007 (POSIVA 2007-05)</td>
</tr>
<tr>
<td></td>
<td>Luukkonen 2007 (WR 2006-107)</td>
</tr>
<tr>
<td></td>
<td>Pedersen 2008 (POSIVA 2008-02)</td>
</tr>
<tr>
<td></td>
<td>Pedersen et al. 2007 (WR 2008-34)</td>
</tr>
<tr>
<td></td>
<td>Waber et. al. 2007 (WR 2006-103)</td>
</tr>
</tbody>
</table>
Appendix 2-5. The list of rock mechanics investigations carried out at Olkiluoto. References to reports published since Site Description 2006 (Posiva 2007) is shown in bold in the list.

<table>
<thead>
<tr>
<th>Investigations</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock stress</td>
<td>Klasson &amp; Lejon 1990 (YJT-90-18)</td>
</tr>
<tr>
<td></td>
<td>Ljunggren &amp; Klasson 1996 (PATU-96-26e)</td>
</tr>
<tr>
<td></td>
<td>Malmlund &amp; Johansson 2002 (WR 2002-47)</td>
</tr>
<tr>
<td></td>
<td>Sjöberg 2003 (WR 2003-60)</td>
</tr>
<tr>
<td></td>
<td>Geological Survey of Finland 2005 (Report P 34.4.042)</td>
</tr>
<tr>
<td></td>
<td>Lehtonen 2005 (WR 2005-67)</td>
</tr>
<tr>
<td></td>
<td>Hakala 2006 (POSIVA 2006-03)</td>
</tr>
<tr>
<td></td>
<td><strong>Fecker 2007</strong> (WR 2007-26)</td>
</tr>
<tr>
<td></td>
<td><strong>Lehtonen 2008</strong> (WR 2008-76)</td>
</tr>
<tr>
<td></td>
<td><strong>Berg &amp; Sjöberg 2008</strong> (WR 2008-xx)</td>
</tr>
<tr>
<td></td>
<td>Ask (WR 2009-xx)</td>
</tr>
<tr>
<td>Mechanical properties of the intact rock</td>
<td>Matikainen &amp; Simonen 1992 (TVO WR 92-36)</td>
</tr>
<tr>
<td></td>
<td>Kuula 1994 (TEKA-94-13)</td>
</tr>
<tr>
<td></td>
<td>Johansson &amp; Autio 1995 (TEKA-95-19)</td>
</tr>
<tr>
<td></td>
<td>Tolppanen et al. 1995 (YJT-95-11)</td>
</tr>
<tr>
<td></td>
<td>Hakala &amp; Heikkilä 1997a (POSIVA-97-04)</td>
</tr>
<tr>
<td></td>
<td>Hakala &amp; Heikkilä 1997b (POSIVA-97-07e)</td>
</tr>
<tr>
<td></td>
<td>Wanne 2002 (POSIVA 2002-05)</td>
</tr>
<tr>
<td></td>
<td>Pohjanperä et al. 2005 (WR 2005-59)</td>
</tr>
<tr>
<td></td>
<td>Hakala et al. 2005 (WR 2005-61)</td>
</tr>
<tr>
<td></td>
<td>Eloranta 2006 (WR 2006-80)</td>
</tr>
<tr>
<td></td>
<td>Niinimäki &amp; Aaltonen 2006 (WR 2006-106)</td>
</tr>
<tr>
<td></td>
<td>Hagros et al. 2007 (WR 2008-68)</td>
</tr>
<tr>
<td></td>
<td>Ojala &amp; Stenebrätten 2008 (WR 2008-27)</td>
</tr>
<tr>
<td>Thermal properties of the intact rock</td>
<td>Kjorholt 1992 (TVO WR 92-56)</td>
</tr>
<tr>
<td></td>
<td>Kukkonen &amp; Lindberg 1995 (YJT-95-08)</td>
</tr>
<tr>
<td></td>
<td>Kukkonen &amp; Lindberg 1998 (WR 98-09e)</td>
</tr>
<tr>
<td></td>
<td>Kukkonen 2000 (WR 2000-40)</td>
</tr>
<tr>
<td></td>
<td>Kukkonen &amp; Suppala 1999 (POSIVA 99-01)</td>
</tr>
<tr>
<td></td>
<td>Kukkonen et al. 2000 (WR 2000-25)</td>
</tr>
<tr>
<td></td>
<td>Kukkonen et al. 2001 (WR 2001-23)</td>
</tr>
<tr>
<td></td>
<td>Huotari &amp; Kukkonen 2004 (WR 2004-04)</td>
</tr>
<tr>
<td></td>
<td>Suppala et al. 2004 (WR 2004-20)</td>
</tr>
<tr>
<td></td>
<td>Kukkonen et al. 2005 (WR 2005-09)</td>
</tr>
<tr>
<td></td>
<td><strong>Kukkonen et al. 2007</strong> (POSIVA 2007-01)</td>
</tr>
<tr>
<td></td>
<td><strong>Kukkonen et al. (POSIVA 2009-xx)</strong></td>
</tr>
<tr>
<td>Mechanical properties of fractures</td>
<td>Kuula &amp; Johansson 1991 (YJT-91-03)</td>
</tr>
<tr>
<td></td>
<td>Hakala et al. 1993 (YJT-93-06)</td>
</tr>
<tr>
<td></td>
<td>Rautakorpi et al. 2003 (WR 2003-09)</td>
</tr>
<tr>
<td></td>
<td><strong>Kuula et al. (WR 2009-xx)</strong></td>
</tr>
<tr>
<td>Mechanical properties of deformation zones</td>
<td>Aikäs et al. 2000 (POSIVA 2000-08)</td>
</tr>
<tr>
<td></td>
<td><strong>Hudson et al. 2008</strong> (WR 2008-67)</td>
</tr>
<tr>
<td></td>
<td><strong>Kuula et al. (WR 2009-xx)</strong></td>
</tr>
<tr>
<td>Mechanical properties of the rock mass</td>
<td>Aikäs et al. 2000 (POSIVA 2000-08)</td>
</tr>
<tr>
<td></td>
<td>Drilling reports of KRs and PHs</td>
</tr>
<tr>
<td></td>
<td><strong>Öhman et al. (WR 2008-18)</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Remes et al. (WR 2009-xx)</strong></td>
</tr>
<tr>
<td>MS and GPS and surface levelling measurements</td>
<td>Chen &amp; Kakkuri 1994 (YJT-94-02)</td>
</tr>
<tr>
<td></td>
<td>Chen &amp; Kakkuri 1995 (PATU-95-30e)</td>
</tr>
<tr>
<td></td>
<td>Saari 2003 (WR 2003-37)</td>
</tr>
<tr>
<td></td>
<td>Ollikainen et al. 2004 (WR 2004-12)</td>
</tr>
</tbody>
</table>
Lehmuskoski 2004 (WR 2004-07)
Riikonen 2005 (WR 2005-30)
Ahola et al. 2005 (WR 2005-41)
Saari 2005 (WR 2005-48)
Riikonen 2006 (WR 2006-66)
Mattila 2007 (WR 2007-53)
Saari & Lakio 2007 (WR 2007-55)
Ahola et al. 2007 (WR 2007-56)
Lehmuskoski 2008 (WR 2008-19)
Saari & Lakio 2008 (WR 2008-39)
Ahola et al. 2008 (WR 2008-35)
Mattila & Hakala 2008 (WR 2008-22)
### Appendix 4-I. Geological data from surface outcrops and investigation trenches at Olkiluoto used in GSM v1.0: investigations, types of data, references and data sources (Mattila et al. 2008).

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Type of data</th>
<th>Reference</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrographic and mineralogical study at the Ulkopää site</td>
<td>Lithological mapping, microscopic investigations</td>
<td>Lindberg (1986)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Bedrock and fracture mapping</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Paulamäki (1989)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Interpretation of the geological structures</td>
<td>Mapping of structures of the ductile deformation</td>
<td>Paulamäki &amp; Koistinen (1991)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Fracture mapping above the VLJ repository</td>
<td>Fracture mapping</td>
<td>Sacklén (1994)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK1</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Paulamäki (1995)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of two sludge basins</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Aikäs (1995)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK2</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Paulamäki (1996)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of construction site of OL3</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Talikka (2005a)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK4</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Paulamäki (2005a)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK5 and TK6</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Paulamäki &amp; Aaltonen (2005)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK7</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Paulamäki (2005b)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of ONKALO open cut</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Talikka (2005b)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK8</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Engström (2006)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK9</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Nordbäck &amp; Talikka (2006)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Dating of tonalitic gneiss, pegmatitic granite and diabase dyke</td>
<td>Petrographic and geochemical investigations</td>
<td>Mänttäri et al. (2006)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK11</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Mattila et al. (2007)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK12</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Nordbäck &amp; Engström (2007)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of investigation trench TK13</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Talikka (2007)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Geological mapping of the Olkiluoto region</td>
<td>Mapping of structures of the ductile and brittle deformation within the migmatite area and the Eurajoki rapakivi stock</td>
<td>Paulamäki (2007)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Structural mapping on islands surrounding Olkiluoto</td>
<td>Search for post-glacial faults</td>
<td>Lindberg (2007)</td>
<td>Surface-based</td>
</tr>
</tbody>
</table>
### Appendix 4-2. Geological data from surface-based drillholes at Olkiluoto used in GSM v1.0 (Mattila et al. 2008): investigations, types of data, references and data sources.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Type of data</th>
<th>Reference</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling of deep drillhole OL-KR1</td>
<td>Standard geological and engineering geological logging</td>
<td>Suomen Malmi (1989b)</td>
<td>Surface-based drillhole</td>
</tr>
<tr>
<td>Drilling of deep drillhole OL-KR9</td>
<td>Standard geological and engineering geological logging</td>
<td>Rautio (1996b)</td>
<td>Surface-based drillhole</td>
</tr>
<tr>
<td>Drilling of deep drillhole OL-KR14</td>
<td>Standard geological and engineering geological logging</td>
<td>Niinimäki (2001b)</td>
<td>Surface-based drillhole</td>
</tr>
<tr>
<td>Drilling of deep drillhole OL-KR16</td>
<td>Standard geological and engineering geological logging</td>
<td>Niinimäki (2002b)</td>
<td>Surface-based drillhole</td>
</tr>
<tr>
<td>Drilling of deep drillhole OL-KR17</td>
<td>Standard geological and engineering geological logging</td>
<td>Niinimäki (2002c)</td>
<td>Surface-based drillhole</td>
</tr>
<tr>
<td>Drilling of deep drillhole OL-KR19</td>
<td>Standard geological and engineering geological logging</td>
<td>Niinimäki (2002e)</td>
<td>Surface-based drillhole</td>
</tr>
<tr>
<td>Drilling of deep drillhole OL-KR21</td>
<td>Standard geological and engineering geological logging</td>
<td>Niinimäki (2002g)</td>
<td>Surface-based drillhole</td>
</tr>
<tr>
<td>Drilling of deep drillhole OL-KR26</td>
<td>Standard geological and engineering geological logging</td>
<td>Niinimäki (2003c)</td>
<td>Surface-based drillhole</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>------------------------------------------</td>
<td>---------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Drilling of deep drillhole OL-KR34</td>
<td>Standard geological and engineering logging</td>
<td>Rautio (2005c)</td>
<td>Surface-based drillhole</td>
</tr>
<tr>
<td>Dating of fracture minerals, drillhole KR1</td>
<td>Petrographic, geochemical and geophysical investigations</td>
<td>Blomqvist et al. (1992)</td>
<td>Surface-based drillhole</td>
</tr>
<tr>
<td>Petrology and low temperature fracture minerals, drillhole KR9</td>
<td>Petrographic, geochemical and geophysical investigations</td>
<td>Gehör et al. (1997)</td>
<td>Surface-based drillhole</td>
</tr>
<tr>
<td>Isotopic and fluid inclusion study of fracture calcite, drillhole KR1</td>
<td>Petrographic, geochemical and geophysical investigations</td>
<td>Blyth et al. (1998)</td>
<td>Surface-based drillhole</td>
</tr>
<tr>
<td>Shallow drillings by IVO</td>
<td>Standard geological and engineering logging</td>
<td>Imatran Voima (1974), Jokinen (1990a)</td>
<td>Surface-based drillhole</td>
</tr>
</tbody>
</table>
Appendix 4-3. Geological data from pilot holes at Olkiluoto used in GSM v1.0 (Mattila et al. 2008): investigations, types of data, references and data sources.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Type of data</th>
<th>Reference</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling of pilot hole OL-PH1</td>
<td>Standard geological and engineering geological logging</td>
<td>Niinimäki (2004a)</td>
<td>Underground-based drillholes</td>
</tr>
<tr>
<td>Drilling of pilot hole ONK-PH2</td>
<td>Standard geological and engineering geological logging</td>
<td>Öhberg et al. (2005)</td>
<td>Underground-based drillholes</td>
</tr>
<tr>
<td>Drilling of pilot hole ONK-PH3</td>
<td>Standard geological and engineering geological logging</td>
<td>Öhberg et al. (2006a)</td>
<td>Underground-based drillholes</td>
</tr>
<tr>
<td>Drilling of pilot hole ONK-PH4</td>
<td>Standard geological and engineering geological logging</td>
<td>Öhberg et al. (2006b)</td>
<td>Underground-based drillholes</td>
</tr>
<tr>
<td>Drilling of pilot hole ONK-PH5</td>
<td>Standard geological and engineering geological logging</td>
<td>Öhberg et al. (2006c)</td>
<td>Underground-based drillholes</td>
</tr>
</tbody>
</table>

Appendix 4-4. Geological data from the VLJ repository - analogue underground data from a location near the Olkiluoto site used in GSM v1.0 (Mattila et al. 2008): investigations, types of data, references and data sources.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Type of data</th>
<th>Reference</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering geological mapping of the access tunnel of the VLJ repository</td>
<td>Engineering geological mapping</td>
<td>Ikävalko &amp; Niskanen (1989a,b)</td>
<td>Underground-based</td>
</tr>
<tr>
<td>Petrography and Petrophysics, VLJ repository</td>
<td>Petrographic and geophysical investigations</td>
<td>Lindberg &amp; Paananen (1991b)</td>
<td>Underground-based</td>
</tr>
<tr>
<td>Fracture mapping of the research tunnel in the VLJ repository</td>
<td>Engineering geological mapping</td>
<td>Äikäs &amp; Sacklén (1993)</td>
<td>Underground-based</td>
</tr>
<tr>
<td>Analysis of fracture data from the VLJ tunnel</td>
<td>Geological mapping</td>
<td>Front &amp; Kontio (1994)</td>
<td>Underground-based</td>
</tr>
<tr>
<td>Study of porous pegmatite in the VLJ repository</td>
<td>Petrographic and geochemical investigations</td>
<td>Front &amp; Pitkänen (1991)</td>
<td>Underground-based</td>
</tr>
</tbody>
</table>
**Appendix 4-5.** Geophysical data from surface-based (including both airborne and ground surveys) at Olkiluoto used in GSM v1.0 (Mattila et al. 2008): investigations, types of data, references and data sources.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Type of data</th>
<th>Reference</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic and EM interpretation: magnetized units, rock types and electric conductors</td>
<td>Airborne geophysics</td>
<td>Paananen &amp; Kurimo (1990)</td>
<td>Surface-based</td>
</tr>
<tr>
<td></td>
<td>Ground geophysics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lineament interpretation</td>
<td>Airborne geophysics</td>
<td>Paulamäki &amp; Paananen (2001)</td>
<td>Surface-based</td>
</tr>
<tr>
<td></td>
<td>Ground geophysics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lineament interpretation</td>
<td>Airborne geophysics</td>
<td>Paalanäki et al. (2002)</td>
<td>Surface-based</td>
</tr>
<tr>
<td></td>
<td>Ground geophysics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lineament interpretation</td>
<td>Airborne geophysics</td>
<td>Korhonen et al. (2005)</td>
<td>Surface-based</td>
</tr>
<tr>
<td></td>
<td>Ground geophysics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geophysical ground level survey</td>
<td>Ground geophysics</td>
<td>Suomen Malmi Oy (1989a)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Magnetic and EM investigations</td>
<td>Ground geophysics</td>
<td>Lahti (2004)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Seismic refraction</td>
<td>Ground geophysics</td>
<td>Lehtimäki (2003a,b)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Refraction seismic investigation in OL-TK3 area</td>
<td>Ground geophysics</td>
<td>Ihlanen (2005)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Wide-band electromagnetic soundings</td>
<td>Ground geophysics</td>
<td>Jokinen (1990b)</td>
<td>Surface-based</td>
</tr>
<tr>
<td></td>
<td>Ahokas (2003)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radar soundings</td>
<td>Ground geophysics</td>
<td>Koskiahde (1988)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>Petrophysical data</td>
<td>Ground geophysics</td>
<td>Paananen &amp; Kurimo (1990)</td>
<td>Surface-based</td>
</tr>
<tr>
<td>3D surface seismics</td>
<td>Ground geophysics</td>
<td>Paananen (2004)</td>
<td>Surface-based</td>
</tr>
<tr>
<td></td>
<td>Juhlin &amp; Cosma (2007)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Appendix 4-6. Geophysical data from surface-based drillholes at Olkiluoto used in GSM v1.0 (Mattila et al. 2008): investigations, types of data, references and data sources.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Type of data</th>
<th>Reference</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drillhole gamma-ray spectrum logging of OL-KR4</td>
<td>Single-hole geophysics</td>
<td>Julkunen &amp; Kallio (2005a,b)</td>
<td>Surface-based drillholes</td>
</tr>
<tr>
<td>Geophysical drillhole logging at Olkiluoto, dual neutron and full waveform sonic log</td>
<td>Single-hole geophysics</td>
<td>Lowit et al. (1996)</td>
<td>Surface-based drillholes</td>
</tr>
<tr>
<td>Visualisation and interpretation of year 2004 mise-à-la-masse survey data</td>
<td>Mise-à-la-masse</td>
<td>Lehtonen (2006a)</td>
<td>Surface-based drillholes</td>
</tr>
<tr>
<td>Visualisation and interpretation of year 2005 mise-à-la-masse survey data</td>
<td>Mise-à-la-masse</td>
<td>Lehtonen (2006b)</td>
<td>Surface-based drillholes</td>
</tr>
<tr>
<td>Cross-hole correlation of the MAM results</td>
<td>Mise-à-la-masse</td>
<td>Paananen et al. (2007)</td>
<td>Surface-based drillholes</td>
</tr>
<tr>
<td>VSP and HSP in Olkiluoto 2002</td>
<td>Seismic drillhole measurements</td>
<td>Cosma et al. (2003)</td>
<td>Surface-based drillholes</td>
</tr>
<tr>
<td>Reflection seismics using drillholes at Olkiluoto in 2003</td>
<td>Seismic drillhole measurements</td>
<td>Heikkinen et al. (2004a, 2004c)</td>
<td>Surface-based drillholes</td>
</tr>
<tr>
<td>Reflection seismics using drillholes at Olkiluoto in 2003</td>
<td>Seismic drillhole measurements</td>
<td>Enescu et al. (2004)</td>
<td>Surface-based drillholes</td>
</tr>
<tr>
<td>VSP and crosshole investigations in Olkiluoto 2002</td>
<td>Seismic drillhole measurements</td>
<td>Enescu et al. (2003)</td>
<td>Surface-based drillholes</td>
</tr>
</tbody>
</table>
Appendix 4-7. Other sources of data used in GSM v1.0 (Mattila et al. 2008): investigations, types of data and references.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Type of data</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Literature survey on the structure and geological evolution of the bedrock in southern Satakunta</td>
<td>Literature compilation and interpretation of the aemagnetic lineaments</td>
<td>Paulamäki et al. 2002</td>
</tr>
<tr>
<td>Lineament interpretation</td>
<td>Interpretation of the topographic data</td>
<td>Kuivamäki (2000)</td>
</tr>
<tr>
<td>Lineament interpretation</td>
<td>Interpretation of the topographic data</td>
<td>Kuivamäki (2001)</td>
</tr>
<tr>
<td>Literature survey on the characterisation of brittle deformation at Olkiluoto</td>
<td>Literature compilation</td>
<td>Milnes (2006)</td>
</tr>
<tr>
<td>Literature survey on the geological evolution of the Fennoscandian shield during the last 1300 years.</td>
<td>Literature compilation</td>
<td>Paulamäki &amp; Kuivamäki (2006)</td>
</tr>
<tr>
<td>U-Pb ages for rock types at Olkiluoto</td>
<td>Age determination</td>
<td>Mänttäri et al. (2006)</td>
</tr>
<tr>
<td>U-Pb ages for rock types from OL-T13</td>
<td>Age determination</td>
<td>Mänttäri et al. (2005)</td>
</tr>
<tr>
<td>K-Ar age determination for fault breccia samples</td>
<td>Age determination</td>
<td>Mänttäri et al. (2007b)</td>
</tr>
<tr>
<td>Characterisation of foliation at Olkiluoto</td>
<td>Methodology for the characterisation of foliation at Olkiluoto and results of pilot studies</td>
<td>Milnes et al. (2006), Palmen (2004), Aaltonen (2005)</td>
</tr>
<tr>
<td>Regional lineament analysis</td>
<td>Interpretation of the topographic and airborne magnetic data</td>
<td>Paananen &amp; Kuivamäki (2007)</td>
</tr>
</tbody>
</table>

Appendix 4-8. Surface-based geological data at Olkiluoto, used in site description 2008 after the completion of GSM v1.0 (Mattila et al. 2008): investigation, type of data, reference and data source.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Type of data</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geological mapping of investigation trench TK14</td>
<td>Mapping of lithologies, structures of the ductile deformation and fractures</td>
<td>Nordbäck (2008)</td>
</tr>
</tbody>
</table>

Appendix 4-9. Geological data from surface-based drillholes at Olkiluoto used in site description 2008 after the completion of GSM v1.0 (Mattila et al. 2008): investigations, types of data, references and data sources.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Type of data</th>
<th>Reference</th>
</tr>
</thead>
</table>

Appendix 4-10. Surface-based geophysical data from Olkiluoto, used in site description 2008 after the completion of GSM v1.0 (Mattila et al. 2008): investigation, type of data, reference and data source.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Type of data</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D surface seisms, 2007 survey</td>
<td>Ground geophysics</td>
<td>Cosma et al. (2008)</td>
</tr>
</tbody>
</table>
**Appendix 4-11.** Geophysical data from surface-based drillholes in Olkiluoto, used in site description 2008 after the completion of GSM v1.0 (Mattila et al. 2008): investigations, types of data, references and data sources.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Type of data</th>
<th>Reference</th>
<th>Source</th>
</tr>
</thead>
</table>

**Appendix 4-12.** Geophysical data from tunnel drillholes in Olkiluoto, used in site description 2008 after the completion of GSM v1.0 (Mattila et al. 2008): investigations, types of data, references and data sources.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Type of data</th>
<th>Reference</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geophysical drillhole logging of ONK-PH6</td>
<td>Single-hole geophysics</td>
<td>Öhberg et al. (2007a)</td>
<td>Underground-based drillholes</td>
</tr>
<tr>
<td>Geophysical drillhole logging of ONK-PH7</td>
<td>Single-hole geophysics</td>
<td>Öhberg et al. (2007b)</td>
<td>Underground-based drillholes</td>
</tr>
</tbody>
</table>
UNCERTAINTY AND CONFIDENCE ASSESSMENT

Appendix 10-1. Addressing the needs of the Safety case.

Before considering the confidence and uncertainties in the site description, it is important to consider what aspects of the site description that are judged needed for the Safety Case. These needs can be derived from the overall safety functions of the geosphere, the rock properties contributing to fulfilment of the safety functions and processes affecting these properties. The safety functions of the geosphere are defined to be (Posiva 2003, Posiva 2006, and Vieno & Ikonen 2005 and recently Posiva 2008):

- to isolate the repository from the biosphere and normal human habitat
- to provide favourable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers and to protect them from potentially detrimental processes taking place above and near the ground surface and
- to limit and retard inflow and release of harmful substances to and from the repository.

The site description should provide information (process understanding and data) needed for conceptualisation and modelling of the processes affecting the safety functions. Miller & Marcos (2007) give a summary of the processes affecting the site and repository evolution and migration of radionuclides and other substances. The rock properties and their value ranges, defining the conditions that contribute to the fulfilment of the safety functions of the geosphere, are currently being developed. Practical criteria (Rock suitability criteria, RSC) to select rock volumes that are likely to provide the desired rock properties in long term, and that are thus suitable for hosting deposition holes, are being developed within the rock suitability criteria (RSC) programme. According to the Safety Case Plan (Posiva 2008), the models and data used for describing the evolution of the site and the repository and the safety assessment will be summarised in what are known as the Models and Data Reports. These reports will include discussions of the uncertainties and the abstractions and simplifications needed and their impact on the results of the safety assessment. The first such Models and Data Report will be published in 2009 and the second in 2012, with the first concentrating on data used in the recent safety assessments (for KBS-3H, Smith & al 2008 and for KBS-3V, Nykyri et al. 2008). The site description provides important inputs for these and other Safety Case reports.

Table 10-1 lists the information the Safety Case is expecting from the Site Description, indicates whether this information is provided by Site Report 2008, and, if not, indicates the other reports that should provide the data. It is noted that the Site model discusses the current and past conditions of the site and the impact of the construction of the ONKALO. The future evolution of the site and repository and radionuclide transport will be covered by reports produced according to the Safety Case Plan (Posiva 2008). The main reports, in addition to the Models and Data report, are: Description of the Disposal System, Process, Formulation of Scenarios (including repository evolution), Analyses of Scenarios (including radionuclide transport calculations), Complementary Considerations, and Summary Report.
Table 10-1. Site specific information needed for compilation of safety case and its handling in Site Report 2008.

<table>
<thead>
<tr>
<th>ID</th>
<th>Safety Case needs</th>
<th>How handled in Site Report 2008</th>
<th>If not handled in Site Report 2008, where is it handled?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Groundwater composition</strong></td>
<td>Used in safety case to <em>analyse canister corrosion</em> <em>analyse buffer and backfill behaviour</em> <em>evolution of the groundwater composition and buffering capacity of the rock</em> <em>define migration properties</em></td>
<td>Prediction of future evolution of groundwater composition is part of description of the site evolution. Reference groundwater conditions during the assessment period will be summarised in the Models and Data reports. The reference groundwaters are needed also for e.g. testing performance of the buffer and laboratory studies of e.g. solubilities and sorption parameters.</td>
</tr>
<tr>
<td>S1</td>
<td>Groundwater composition in the near-field and processes affecting the groundwater composition  <em>Salinity - chloride</em>  <em>pH and alkalinity</em>  <em>Ionic strength</em>  <em>Sulphate and sulphide concentrations</em>  <em>Redox environment (O₂, Fe)</em>  <em>Concentration of K</em>⁺  <em>Gases (methane) (also gas generation by structural components, steel etc.)</em>  <em>Colloid concentration</em>  <em>Organics (TOC)</em>  <em>Microbes</em></td>
<td>Current composition as well as explanation for current composition by mixing/reactions are provided in Chapter 7. This process understanding forms the basis for predicting the future groundwater composition.</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>Rock and fracture mineral geochemistry</td>
<td>There is a general discussion on the alteration model in Chapter 4. A synthesis of the distribution of the fracture filling at the site is included in Chapter 4.</td>
<td>May be used for development of the retention models. Complementary considerations may potentially use information available on rock water interactions, fracture mineralogy and groundwater composition for argumentation of stable groundwater conditions at the site.</td>
</tr>
</tbody>
</table>

**Deformation zones and fracturing** | Will be used in Safety Case for:  
- *Input for flow and transport modelling (HYDRO-DFN)*  
- *THM modelling of the near field (rock) e.g. THM (C) process modelling of rock fracturing induced by thermal stresses, gas, saturation and swelling of bentonite*  
- *Earthquake risk analysis* | |

| S3 | Deformation zones | Are provided in the geological model in Chapter 4 and by the hydrostructure model of Chapter 6 | The Site Report with its background reports is the main source of information of deformation zones, their location and properties. Within RSC programme further assessment of the deformation zones and their properties, including definition of the respect distances and how they affect the repository layout will be carried out. Of special interest are the potential of zones to host earthquakes and zones and fractures that may undergo secondary displacements. |
Cases analysing the impact of shear movements occurring during the post-glacial period will be included in the radionuclide transport analysis.

<table>
<thead>
<tr>
<th>S4</th>
<th>Fracturing:</th>
<th>A description of all fractures is provided by the Geological-DFN model summarised in Chapter 4. A description of the transmissive fractures are given by the Hydrogeological DFN-model, summarised in Chapter 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracturing:</td>
<td>Geometry:</td>
<td></td>
</tr>
<tr>
<td>Geometry</td>
<td>- Orientation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Size</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Intensity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Spatial structure</td>
<td></td>
</tr>
<tr>
<td>Properties:</td>
<td>Mineralogy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Hydraulic (especially connected transmissivity)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and retention properties, (see flow and migration properties below)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flow related properties</th>
<th>Will be used in Safety Case for</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow modelling (near and far field)</td>
</tr>
<tr>
<td></td>
<td>Solute transport modelling</td>
</tr>
<tr>
<td></td>
<td>Description of evolution of the hydrogeochemical environment and EBS, including saturation and swelling of the bentonite</td>
</tr>
<tr>
<td></td>
<td>Release points and recharge areas input for the biosphere assessment</td>
</tr>
<tr>
<td>S5</td>
<td>Groundwater flow at the site and in a more detail scale suitable for assessing flow around deposition holes</td>
</tr>
<tr>
<td>S6</td>
<td>Boundary conditions</td>
</tr>
</tbody>
</table>

| S7 | Flow related migration properties:  - (Equivalent) flow rates (see also above)  - Hydrodynamic control/transport | Addressed in Chapter 8 Detailed description of the flowing features and their environment like mineralogy, alteration etc. that can affect the flow and transport properties and needed for conceptualisation of the retention Future conditions will be evaluated as part of the description of the site and repository evolution. Reference values (e.g. equivalent flow rates) | Future conditions will be evaluated as part of the description of the site and repository evolution. Reference values (e.g. equivalent flow rates) |

**Migration properties**

*Will be used in Safety Case for analysis of radionuclide transport*
<table>
<thead>
<tr>
<th>S8</th>
<th>Matrix related migration properties</th>
<th>Site specific data on porosity and effective diffusion coefficient are given in Chapter 8.</th>
<th>Distribution coefficients will be discussed in separate background reports based on literature, laboratory and potential in situ tests. The data to be used in safety assessments will be summarised in the Models and Data reports.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S8</td>
<td>Porosity</td>
<td></td>
<td>Distribution coefficients will be discussed in separate background reports based on literature, laboratory and potential in situ tests. The data to be used in safety assessments will be summarised in the Models and Data reports.</td>
</tr>
<tr>
<td>S8</td>
<td>Effective diffusion</td>
<td></td>
<td>Distribution coefficients will be discussed in separate background reports based on literature, laboratory and potential in situ tests. The data to be used in safety assessments will be summarised in the Models and Data reports.</td>
</tr>
<tr>
<td>S8</td>
<td>Distribution coefficients</td>
<td></td>
<td>Distribution coefficients will be discussed in separate background reports based on literature, laboratory and potential in situ tests. The data to be used in safety assessments will be summarised in the Models and Data reports.</td>
</tr>
<tr>
<td>S9</td>
<td>Stress state</td>
<td>Current stress state is provided in Chapter 5. Future stress state will depend on future loads (thermal, glacial etc.) This is not assessed in the Site Report but these additional stress states are predictable.</td>
<td>Evolution of stress state should be discussed as part of the site and repository evolution including impact of the periodic loading and unloading induced by glaciations.</td>
</tr>
<tr>
<td>S10</td>
<td>Rock strength and deformation properties</td>
<td>Basic stress and strength data are presented in Chapter 5. The potential for spalling during construction is addressed in Chapter 9.</td>
<td>The impact of the construction and any changes due to processes (e.g. spalling, formation of EDZ) occurring in the future will be discussed as part of the description of the site and repository evolution. Summary of the properties will be given in the Models and Data reports.</td>
</tr>
</tbody>
</table>

**Rock mechanics**

`THM modelling of the near field (rock) e.g. THM (C) process modelling of rock fracturing induced by thermal stresses, gas and bentonite swelling, analysis of the earthquake risks`
<table>
<thead>
<tr>
<th><strong>Thermal properties</strong></th>
<th>Will be used in Safety Case for</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• THM Evolution of the near field (rock)</td>
</tr>
<tr>
<td></td>
<td>• estimation of the impacts of permafrost</td>
</tr>
<tr>
<td></td>
<td>• Also important for thermal dimensioning of the repository</td>
</tr>
</tbody>
</table>

| S11 | Initial temperature | Is provided in Chapter 5. |
|     | Thermal conductivity, | Evolution of the rock temperature will be discussed as part of the description of the site and repository evolution, including also periods of permafrost and glaciation |
|     | Thermal diffusivity, | |
|     | Heat capacity | |
|     | Regional heat flow | |

| **Impacts from underground construction** | In the Safety Case there is a need to assess the impact of the underground construction on the EBS and the rock properties which affect their evolution or radionuclide transport. |

| S12 | EDZ | |
|     | • extent of EDZ and | |
|     | • hydraulic properties of the EDZ | |
|     | Assessment of the EDZ around existing ONKALO tunnels is presented in Chapter 9. | Will be discussed also as part of the site and repository evolution, the impact on inflow to and flow rates around the deposition holes and on radionuclide transport needs to be evaluated and may potentially affect the repository design and operation. |

| S13 | Thermally-induced spalling | Is not assessed, since it depends on details of the repository layout. The Site Report provides the required site input data for making an assessment of thermally-induced spalling |
|     | | Thermally-induced spalling is analysed in more detail in spalling analysis (rock mechanics) reports. |
|     | | Will be assessed and discussed as part of the repository evolution. The significance |
Regarding inflow to and flow rates around the deposition holes and to radionuclide transport needs to be evaluated and may potentially affect the repository design and operation.

| S14 | Inflows | Is assessed (Section 9.4), but not at deposition hole scale. Process understanding that is gained based on analysing e.g. monitoring effect of the excavations to be included. Improved site description. | Estimation of the inflows to deposition holes and tunnels is needed for e.g. analysis of the buffer and backfill performance. The inflow during the operational phase will be discussed also as part of the site repository evolution. Summary of the inflow will be included in the Models and Data report. |
| S15 | Construction related materials (including cement) | Not assessed. Amount, Transport, Interaction with EBS, Interaction with geosphere, Grouting holes and their role in the groundwater flow and transport, Degradation of boreholes seals and plugs their role in the groundwater flow and transport, Impact on groundwater composition | Amounts of stray materials will be summarised in the Models and Data report. Assessment of the impact of the construction, incl. introduction of stray material, esp. cement, will be part of the discussion of the site and repository evolution. Impact of stray materials on the EBS will be studied as part of the performance assessment of the engineered components and the description of the site and repository evolution. Migration of stray materials, as well as the impact of degrading plugs and seals, will be discussed as part of the site and repository description. |
### S16
**Stress state changes (changing loads due to the excavation)**

Is part of the Rock Mechanics P/O work (see Chapter 9), but the impact of the repository is not assessed, since that would require a repository layout. This will be discussed in more detail in rock mechanics analysis reports and also in the Evolution report.

### Site Synthesis

*Contributes to the Safety Case by providing the general process understanding and thus input for description of site evolution and radionuclide and other solute migration, also important for assessment of the confidence of the applied models and treatment of the uncertainties.*

### S17
**Demonstration of overall site understanding**

- including assessment of confidence and consistency of the information

Generally assessed in Chapter 10

Models and Data report will discuss the uncertainties related to conceptualisation, modelling and data.

Uncertainties may lead to derivation of scenarios or calculation cases for radionuclide transport assessment to study the impact of the uncertainties.

Further discussion may be included in the Complementary considerations or Summary report of the Safety Case.

### S18
**Site/process understanding**

- **Groundwater flow evolution**
- **Evidence of slow transport in the geosphere**
- **Reducing conditions**

Evidences of limited and retarded inflow and release of harmful substances to and from the repository are not clearly addressed, although could be inferred from the list of remaining critical issues. Consistency with hydrogeology and hydrogeochemistry is important. Buffer capacity of the fracture minerals against oxygen intrusion and "cement".

See above.
<table>
<thead>
<tr>
<th><strong>Salinity evolution</strong></th>
<th>Possibility of using rock mechanics information to back up/ explain observations of flow field or distribution of water types</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sulphate reduction and microbial processes</strong></td>
<td>Studies on correlation of fracture length and transmissivity using ONKALO data</td>
</tr>
<tr>
<td><strong>Gas generation and rate of gas transport</strong></td>
<td>See also discussion under chemistry. Some further overall statements about understanding should be made.</td>
</tr>
<tr>
<td><strong>Features contributing to retention and retardation of radionuclides</strong></td>
<td>Oxygen, sulphate and gas issues and salinity are the focus of the Site Reports. (Process understanding in hydrogeochemistry is actually the basis of evaluating the groundwater composition. Chemical parameters should be based on dynamic models not on constant parameters. cf. hydrogeochemical environment).</td>
</tr>
<tr>
<td><strong>Stable rock mechanics conditions</strong></td>
<td>It seems more important to study buffering capacity for redox and cement than searching for absence of detrimental conditions.</td>
</tr>
</tbody>
</table>

**S19 Predictability of**

- **the bedrock conditions**
- **groundwater conditions and resulting chemical conditions**

From P/O studies; understanding what can we really predict and what the different observations actually tell us (e.g. scaling between tunnel and pilot holes)

Reliable hydrogeochemical models will be developed through P/O studies. Consistency with hydrogeochemistry, hydrogeology and geology should be further improved

Related to confidence in the applied models and will be addressed in the Models and Data reports. Also important for development of the criteria to select the deposition hole locations and thus considered in the RSC programme (DETECT)
Appendix 10-2. Main issues regarding the Olkiluoto site and their handling in Site Model 2008.

As for SR2006, a part of the site modelling presented in SR2008 has been to explore the confidence and remaining uncertainties, if any, within the different subject areas. Generally, the mass of information available allows an elaborate and, at least in the ONKALO volume, very detailed description of the site, but some issues, judged still to require further attention, remain. A series of special cross-disciplinary workshops have taken place, which have aimed at:

- Discussing status of issues identified in SR2006 and, if applicable, identifying additional remaining issues
- Why the issue is important – reference to Table 10-1.
- Explain why this is an issue, i.e. cause of uncertainty, or, if the issue is thought to be close to resolution, reasons to be confident.
- Where discussed in SR2008
- Discussion of the need and type of further actions (e.g. need for more data or modelling activities).

The findings of these evaluations are listed in Table 10-2.
Table 10-2. Main issues regarding the Olkiluoto site and their handling in Site Model 2008.

<table>
<thead>
<tr>
<th>Issue</th>
<th>Why is this relevant? – reference to Table 10-1</th>
<th>Current knowledge</th>
<th>Where discussed in SR2008</th>
<th>Is it necessary to take further action in the future? If so what (more data, more modelling,...)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology hydrogeology issues</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I1: Character of the rock mass in the potential repository volumes</td>
<td>S3, S4, S5, S7, S8, S10, S11</td>
<td>As discussed in Chapters 4 to 6, there is a high level of confidence in the description of the ONKALO volume. The data density is high and the fair agreement between predictions and outcome encourages this confidence (see Chapter 9). The data from the central part of the island (i.e. where the ONKALO and most of current drillholes are located) strongly suggests that there are very few highly transmissive features outside the gently-dipping hydrogeological zones. A consistent picture has been developed that the main transmissive features are confined to the HZ19, HZ20 and HZ21 zones. Based on observations from the ONKALO, sub-vertical faults have been observed and these would be hard to detect with the present investigation drillhole orientations. However, these vertical features are likely to be much less transmissive than the gently-dipping HZs. So far very few transmissive sub-vertical features have been found in the ONKALO, but there is a need to have more data from the ONKALO below HZ20, i.e. in more representative rock, before any more definite conclusion can be drawn. Furthermore, the sub-vertical features may be important from a mechanical point of view, even if they are not transmissive. As already stated, there are substantially fewer data in the</td>
<td>The geological aspects of this are discussed in Chapter 4, the hydrogeological in Chapter 6 and the hydrogeochemical ones in Chapter 7. (see also issue I10).</td>
<td>In order to enhance confidence of the eastern area a few more drillholes, possibly complemented by detailed magnetic surveys, would be useful. Such drillholes are planned for 2009 and beyond.</td>
</tr>
</tbody>
</table>
eastern part of the island.

Three-dimensional seismic data suggest that many aspects of the central part of the island, like the three gently-dipping HZs, can be extrapolated to the east. However, the seismics, as well as surface and magnetic data in the east, show the existence of sub-vertical features, off-setting the gently-dipping zones. These features are potentially connected to Rapakivi granite intrusions. This is not encountered on the central part of the island, and this complicates extrapolation to the east.

The locations of these sub-vertical features have been fairly well established by the geophysics data, but the details of their character or their extent are unknown. Also the hydrogeological data from drillholes OL-KR11 and OL-KR45 suggest that the eastern part is different.

The frequency of transmissive features in the eastern area appears to be as low as in the rock lying between the hydrogeological zones in the central part of the Island. However, this is based on few data and there are no hydraulic data from the sub-vertical features.

| I2: Can we characterise the disposal volume in sufficient detail to allow decisions to be made on the locations of disposal tunnels and deposition holes? | S19 | At the detailed scale there may be features, which are not possible to detect from existing surface-based drillholes, from the ONKALO or from characterisation holes from the ONKALO area. The question is, therefore, if current tools for tunnel observations and predictions of the surrounding rock mass are sufficient to characterise the necessary structures? The reasonable agreement between predictions and outcomes, see Chapter 9, on key aspects regarding the layout of the repository, such as the potential for intersecting layout-determining features, the level of fracturing, the geomechanical conditions and the inflows, demonstrates that we can characterise a volume in sufficient detail, when the underground excavations are close to the volume being investigated, to allow | Chapter 10 | In order to resolve this issue, a focused characterisation programme below HZ20 is planned, including a large coverage of pilot holes. The possibility of more detailed exploration activities, e.g. using several pilot holes in one section, could possibly be studied using investigation niches. |
decisions on the detailed locations of disposal tunnels. Furthermore there are now sufficient data to characterise the potential layout-determining features close to the ONKALO, allowing decisions to be made on the locations of the first disposal panels. There is still an issue, however, regarding the stress levels and stress orientations, as they are still uncertain (see issue I6). Data from below HZ20, especially regarding rock stress, would, therefore, be needed for determining the orientation and detailed design of these panels. Generally, it is judged that there is sufficient capacity to characterise the rock to the necessary level of detail. The RSC programme is, however, still establishing what data will be needed for allowing a decision to be accepted regarding the location and orientation of a deposition tunnel and, similarly, for accepting a decision on the location of a deposition hole. Questions remain regarding the details of the data that would be required to allow such decisions to be officially accepted, and how to make most efficient use of site understanding in this regard. More consideration needs also to be given as to when data need to be available for influencing such decisions.

<table>
<thead>
<tr>
<th>S3, S4</th>
<th>Chapter 4.</th>
<th>A conceptual model now exists, but it should be further developed in such a way that the modelled features can be constrained in a more rigorous manner (extent, age relationships etc.). Also, even more use could be made of the ONKALO data, assessing them in more detail, in combination with regional geological data. $^{40}$Ar/$^{39}$Ar studies have been initiated - these could provide information on the different cooling ages of the blocks and thus on the potential for brittle deformation without faulting.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I3: Geological Understanding of the Deformation History</strong></td>
<td>The lithological evolution and the ductile deformation history were already rather well understood in SR2006; and since SR2006 there have also been advances in the understanding of the brittle deformation evolution. There has also been an extensive discussion with the hydrogeology team on the understanding of deformation zones. Some uncertainties remain:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>* There are still some uncertainties related to the association of brittle deformation and the Rapakivi formation to the east (see issue I1).</td>
<td></td>
</tr>
<tr>
<td></td>
<td>* It is not yet firmly established whether there exist brittle deformation zones where there have been no faulting (i.e. joint zones).</td>
<td></td>
</tr>
</tbody>
</table>
### Connectivity and transmissivity of fracture networks at the site – especially in the potential repository volume

| Chapter 6 | Updated DFN analyses of existing and new hydraulic data from the ONKALO will further enhance confidence. Numerical flow modelling could assess the resulting connectivity for different representations of the fracture network. An interference test carried out at depth, e.g. in an investigation niche, should be considered. Shedding light on this issue would build on a careful detection of the groundwater flow in the drillholes employed in the interference test, as well as on a careful geological characterisation of the fractures intersecting the drillholes. In the course of the experiment, water will be pumped out of or into each drillhole, whilst pressure and flow rate responses are measured in the other drillholes. The analysis of experiments needs to be supported with numerical flow modelling. |

| S4, S5, S7 | Generally, there is a quite high level of confidence in the knowledge of these properties, see Chapter 6: The Posiva Flow Log (PFL) primarily measures the connected transmissive features. There are a lot of such detailed hydraulic data from the ONKALO. The data show that only a few features in drillholes have connected transmissivities greater than $10^{-9}$ m$^2$/s. The Hydrogeological DFN model describes the transmissive fractures between the deterministic HZs. The hydrogeological DFN model is consistent with existing data. There is generally a good level of confidence in the overall hydrostructure model. The SR2006 model has been largely confirmed by the observations made during the excavation of the ONKALO. However, some uncertainties remain:  |

- There are more uncertainties in the eastern part (see I1 above). |
- At the large scale, the data show very sparse hydraulic connections, but there could possibly be more, very local hydraulic connections between closely-spaced drillholes. Such connections do not persist over greater distances. The existing PFL data provide a very good control on the connected fractures, but not on the non-connected, but potentially transmissive fractures. Indirect information on potential local hydraulic connections exist, e.g. from drillhole imaging and core logging, but these data generally overestimate the frequency of such features. Direct |
Information on the latter would require small-scale underground interference tests, i.e. made at a scale where these naturally “isolated” fractures would connect between the induced disturbance and the measurement points. The pressure responses from tunnel construction could also be an indirect source of information on these features. This uncertainty is, at least partly, handled by formulating different alternative hydrogeological DFN models, with different assumptions regarding the frequency of the water-conductive fractures (and the resulting fracture size distribution).

- There is no clear conceptual understanding as to whether only certain fractures are hydraulically important (and then what their characteristics are), due to internal variations in the fracture or due to the poor connectivity of the fracture network. It is probably a combination of both. At any rate, since the densities of isolated inflow points on the ONKALO tunnels are not drastically higher than the expected density of connected transmissive fractures, at least the majority of the flow cannot be concentrated within distinct isolated “worm-like” channels. Furthermore, the impact of channelling on the resulting migration properties can be bounded, see e.g. Crawford (2008).

| **I5: Integration between hydrogeological model and geological model - utilization of hydrogeological data in the construction of the flow model** | S17 | As shown in Chapter 6, the SR2008 large-scale hydrostructure model is now basically consistent with the SR2008 geological model. The changes since SR2006 mainly concern revisions to the geological model, that now also incorporates the information provided by the geophysical data, and does not rely exclusively on strict rules on how faults observed in different drillholes should be connected (which was the situation in SR2006). As part of the interactions between the geological and hydrogeological teams, some modifications have also been made to the details of the hydrostructure model.

The few remaining differences essentially concern areas where the level of confidence is still poor in both models (e.g. in the... | Chapter 6 | The established interaction between the geological and hydrogeological teams will continue. |
eastern part, see issue I1). Also, the geophysical data suggest larger scale connections than are actually observed hydraulically, although this does not necessarily mean that these connections do not exist. The geological model also includes small-scale features that have shown to be hydraulically insignificant. These differences should be no surprise, since the hydraulic properties of geological features vary in space, i.e. we must expect that some geological features should not be hydraulically significant, at least not over their entire areas or volumes.

<table>
<thead>
<tr>
<th>Rock Mechanics / Geology and hydrogeology issues</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I6: Stress distribution and orientation in relation to the geological structures</strong></td>
<td><strong>S9</strong></td>
<td></td>
</tr>
</tbody>
</table>
| At the stage of SR2006 it was noted that a full understanding of the details of the stress distribution was unavailable and the spread and uncertainty in existing rock stress measurements was large. Furthermore, the stress would be affected by the geometry of the geological structures, the mechanical properties of the rock and the stress history. This could also locally affect (i.e. rotate) stress orientations (of potential importance for the orienting the deposition tunnels).

Since SR2006 a limited number of new data have been obtained, including convergence measurements, new in situ stress data from OC (overcoring), compilation of all CD (core discing) observations, strain measurements in the ventilation shaft and observations from the ONKALO tunnels. A semi-integrated stress analysis was also carried out (Ask, expected 2009). The analysis covered all stress data information that was considered of good quality. The following can be noted:

- The new stress measurements using OC at the –230 m level still had problems with the glue – and the measured stress orientations add to the scatter of the already existing OC data.
- The convergence and strain measurements at -180 m level |  | Chapter 5. |
|  |  | Some hydraulic fracturing (HF) data in OL-KR40 and in one ONKALO shaft grouting hole and some acoustic televiewer measurements in OL-KR19, OL-KR40 and OL-KR46, carried out to study borehole breakouts, will be available at the end of 2008. Studying the presence/absence of borehole breakouts could provide some bounding estimates to the stress magnitude. A more definite understanding of the stress will be obtained from the rock mechanics shaft response tests planned below HZ20 and the further observations from the ONKALO. Given the practical difficulties, there is possibly little use in carrying out further drillhole OC tests, but this possibility will still be considered, if the experimental problems can be |
suggest that the orientation of the maximum horizontal stress above HZ20 is N-S rather than the commonly-seen E-W...NW-SE regional orientation; but the stress field may be rotated back to this regional orientation below HZ20.

- ONKALO observations show some occurrences of potential stress-induced failures, but these could also be associated with blast damages and geological structures (i.e. the presence of fractures or a well-developed foliation).

In conclusion, above HZ20 the orientations of the maximum horizontal stress seem to be locally N-S and below HZ20 locally E-W (rather than generally regional plate tectonics orientation NW-SE), possibly due to the relaxation of the stress field above this structure. Below HZ20, the upper bound of the stress is uncertain, and may be higher than indicated by current stress data.

| I7: Properties of intact rock | S10 | As already stated in SR2006, there is a good understanding of the spatial distribution of these properties. The anisotropic strength and deformation characteristics of the rock are quite well understood, and, based admittedly on only a few tests, it has been observed that the altered rock may be as strong as unaltered rock. The lithological model appears to be sufficient for judging the distribution of properties in the potential repository volume; however, some uncertainties remain:
- There may still be some uncertainties regarding the eastern part of the Island (see issue I1).
- Spalling strength data at the necessary scale are currently still based on experience from the Åspö HRL and other URLs, not on site-specific tests.
- Long-term strength properties are generic and based on extrapolation from tests carried out on rock samples in different laboratories throughout the world. |
| I8: Mechanical properties of the brittle deformation | S9, S17 | There is good geological knowledge of the location and geometry of the brittle deformation zones at Okiluoto, and an initial estimate of their mechanical properties has been achieved via Is discussed in Chapter 5 | In order to reduce uncertainty, in situ experiments similar to the ones SKB now conducts at Åspö are planned for below HZ20, where they would be directly relevant to conditions at the repository panels. ONKALO tunnel observations and monitoring will provide further information on the long-term mechanical properties. |
### Zones

The use of rock mass classification. A report (Hudson et al. 2008) has been prepared by the Rock Mechanics OMTF group on a rock mechanics characterisation methodology for the brittle deformation zones. The existing data consist of photos of all the core BDZ intersections in the drillholes, the geological descriptions of these, the Q classification logging data of the cores and Q logging data from tunnel intersections.

The P/O studies presented in Chapter 9 provide a means of correlation and comparison with the data obtained from the BDZs.

Zones from a long-term safety perspective (noting the potentially limited significance of such zones in the near-field). This could now be more worthwhile using the estimated ranges of deformation zone properties as input. The properties are clearly important for the rock mechanics design. The mechanical properties of the brittle deformation zones may be estimated using four methods (in full cooperation with the geological team):

i) empirical evaluation from the core data from the re-logging of the boreholes, the Q' values (see Chapter 5 for explanation of Q') and the photographs;

ii) by numerical modelling;

iii) by indirect seismic measurements; and

iv) by back analysis from observations made in the ONKALO ramp.

### I9: Thermal properties

S11

As further discussed in Chapter 5, there is generally high confidence in the thermal data. Thermal properties are mainly measured in the laboratory on small-scale samples, but additional in situ data are obtained from the TERO probe, that also measures at the more relevant metre scale. Current results suggest quite good correlation between these larger-scale data and the upscaling of the laboratory data, thereby enhancing confidence in the upscaling. Laboratory data suggest some thermal anisotropy, but the potential thermal anisotropy at the larger scale, i.e. the deposition hole and deposition tunnel scales, is not known in detail. Scoping calculations suggest that the

Tests should continue to be carried out on small samples and in situ using the ONKALO tunnel. Below HZ20, it could be useful to carry out a heater experiment (possibly combined with the spalling test discussed above), with detailed temperature monitoring. That would allow further assessment of how to upscale the thermal data to represent the heat conduction at the...
effect of this potential anisotropy, depends on the repository orientation, and that at least for the assessed tunnel orientation in relation to the foliation angle it is not very important for the thermal evolution.

<table>
<thead>
<tr>
<th>Hydrogeochemistry and hydrogeology issues</th>
<th>Chapter 7 Comparison with flow modelling in Chapter 6.</th>
<th>canister scale. Later, during the construction and operation phase of the repository, monitoring of the thermal properties of the rock locally will be necessary for verification of the thermal dimensioning of the repository.</th>
</tr>
</thead>
</table>
| **I10: Distribution of water types and consistency with flow field** | As further discussed in Chapter 7, most water chemistry data are from the HZs and some other connected fractures of relatively high transmissivity. Given the wealth of data and their consistency, we are confident in the distribution and relative residence times of water types in the “flowing part” of the system. New data, including water samples from poorly transmissive fractures and pore waters also support earlier observations, though the salinities are slightly lower than in the more transmissive features. The understanding of residence times and the low fraction of fresh (i.e. very dilute) meltwater, support the idea of a hydrogeological system at Olkiluoto with a strong resistance to external changes. However, some uncertainties remain;

The water type distribution appears to be generally governed by the flow and its variation due to past climate changes. It can be generally reproduced by the hydrogeological simulations, see Chapter 6, but in places in the drillholes some differences between the model predictions and the hydrogeological simulations remain. In these cases the calculated result tends to overestimate the penetration of meteoric water and underestimate the extent of Littorina infiltration. These differences could possibly be reduced by local and detailed scale adjustments in the modelled initial state or the model properties (i.e. flow/diffusion porosity, effective conductivity, etc.) around the HZs.

The following planned or considered actions would help resolving these uncertainties:

- More data are needed from the pores and poorly-connected fracture system. Hydrogeological and chemical investigations and experiments of poorly-transmissive fracture systems are an important step to obtain more information on groundwaters and salinity in different hydrogeological conditions vs. depth.

- Data from the sub-sea drillhole (OL-KR47), pore water and palaeohydrogeological studies will provide further information on the heterogeneity of the distributions of groundwaters and salinities in the past and at the present.

- More data are needed from the poorly-permeable rock, also below HZ20, with continued investigations.
drillholes assessed.

Recent data from the ONKALO indicate that the salinity in poorly-transmissive fractures at the depth of the SO$_4$-rich groundwater layer is slightly lower and the mean residence time longer than in baseline data from the field. It appears, therefore, that the infiltration of Littorina water at these depths has not reached high fractions into the poorly-permeable parts of the rock. However, the groundwater is brackish and relatively older than in the more transmissive fractures sampled from the surface. Pore water studies indicate even lower salinities and longer residence times where diffusion-dominated solute movement exists. However, there are only a few results on pore waters at the moment and more data are needed before a more definitive conclusion can be drawn.

Chemical data also suggest that HZ19 is not a simple infiltration zone, rather it is a mixing and even a discharge zone, at least close to the surface. Chemical data may even suggest that HZ19 is partly isolated, and the possibility needs to be considered as to whether there is any flow at depth within HZ19. Connection to the model boundary is needed for any flow to take place.

There is less knowledge about pore water compositions, i.e. the water inside the rock matrix. A few microbial, porewater and fracture surface data now exist—but more data would be needed before any definite conclusions could be drawn.

Hydrogeological models would need to include all relevant hydraulic features (e.g. as splays of major hydrogeological zones) in order to improve the consistency between the hydrogeological simulations and hydrogeochemistry. This would make it possible to ensure the infiltration of Littorina water into all relatively highly-transmissive features (>10$^{-7}$ m$^2$/s, cf. Figure 7) and would allow the hydraulic conductivity to be decreased in the less permeable parts of the model, thus increasing resistance against meteoric infiltration.

**Evolution of groundwater composition: Flow paths to/from the**

| S1, S17 | As shown in Chapters 3 and 7, the understanding of the connection between the near-surface waters (i.e. surface waters and shallow groundwaters mainly in the overburden) and the waters in the bedrock has advanced due to the development of Chapters 3 and 7 | The infiltration experiment, see I10, will provide relevant data on this issue. Modelling of the near-surface and the rock hydrogeology interface |
**host rock, especially the near-surface interface**

The near-surface hydrogeological modelling. However, some questions remain:

Is there hydraulic anisotropy near the surface? The very high hydraulic anisotropy (of 60) assumed in SR2006 was basically a fitting parameter, with little direct support from any data. In SR2008 it seems that there is less need for assuming such a high anisotropy in the Littorina simulations, although a factor of 10 is still required. Given that the flow is controlled by the fracture system, it would not be unusual to expect an anisotropy to develop. The block-scale hydrogeological DFN simulations do indeed suggest some anisotropy, with higher permeability in the horizontal direction.

With regard to the operational phase, it is noted that inflows generally decrease with time. This is usually attributed to calcite precipitation, but the understanding is incomplete. Probably the carbonate is taken from the surface and the calcium from grouts in the rock. It is the availability of carbonate that limits the formation of calcite.

---

**I12: Evolution of groundwater composition: Impact of surficial water intrusion (pH, Redox and buffering capacity)**

<table>
<thead>
<tr>
<th>S1, S17, S18, S19</th>
</tr>
</thead>
</table>

The status of this issue is essentially the same as in SR2006, but Chapter 7 concludes that more data enhances the level of confidence to some extent. Reducing and neutral hydrogeochemical conditions are clearly buffered in the natural state, but modelling calculations suggest significant consumption of buffering minerals, if aggressive meteoric infiltration is high. Some key uncertainties remain:

- Samples with elevated sulphide concentrations are found. Conceptually, the process of sulphate reduction is clear and is only possible through microbial activity at these temperatures, but the quantification of the microbial activity, particularly the rate of sulphate reduction, is uncertain.

- There are also uncertainties in the flow paths (see I11). This especially concerns conditions during the construction and operational phase, when the possibility of direct flow will continue.

**Chapter 7**

Dealing with this issue includes both numerical flow modelling and in situ monitoring of the chemical composition of water samples and the flow field:

Detailed characterisation and evaluation of fracture minerals (e.g. their buffering capacity, palaeohydrogeochemistry) and pore water is important. An experiment to study meteoric infiltration has started, see I10.

Processes activated by seawater intrusion can be evaluated, using the long-term OL-KR6 pumping test as a...
connections from the sea down to the open tunnels has to be considered. The rate of migration would also depend on the porosity.

- There is evidence that the presence of elevated dissolved sulphides is due to disturbances caused by investigations (e.g. open borehole flow, pumping effects etc.) and in natural conditions mixing between SO$_4^-$ and CH$_4$-rich groundwaters is limited and microbial process stabilised. Isotopic results of stable isotopes indicate that microbial processes have been relatively limited (not pervasive) at the site.

starting point. The analyses of chemical and microbial data integrated with improved hydrogeological understanding around the drillhole is continuing.

A biogeochemical experiment in an investigation niche will be organised just below HZ20 to evaluate SO$_4^-$ reduction due to groundwater mixing. The data on C and S species in groundwater, gases, isotopic compositions and microbes compiled during the experiment may give further details of past processes. The kinetics of microbial SO$_4^-$ reductions have already been tested in reactive transport simulations.

The monitoring programme will also give information on the movements of marine waters and chemical changes.

A palaeohydrogeological evaluation of fracture minerals may give more information from the distribution of microbial sulphate reduction and seawater intrusion in the groundwater system.

Numerical flow modelling should also be able to guide sampling from locations that are anticipated to be experiencing seawater intrusion.
### I13: Evolution of groundwater composition: Formation of gas phase / dissolved gases in groundwater

| S1, S17, S18 | Chapter 7 and previous reports assess the current site knowledge, based on a lot of deep gas samples, and shows that the situation at Olkiluoto is not anomalous, as there are several other locations in the Fennoscandian shield with high methane concentration, which could be the effect of a well-buffered system with reducing conditions. There is a good understanding of the origin of the methane, and there are bacterial and thermal end-members. Bacterial methane is formed at ambient temperatures and has a lower proportion than thermal methane, which is most probably abiogenic and formed at considerably higher temperatures. However, both the current accumulation rate and source of methane production are uncertain, albeit believed to be very slow.  
  
At depth the methane concentration is close to the saturation limit. Secondary fluid inclusions have been observed to contain high methane contents, therefore thermal methane can also have an in situ source and has not necessarily diffused from great depths.  
  
The current rate and source of methane production is unclear. Is its production really common in the upper 1000 m? If it were a fast process, the whole volume should be saturated with methane – but it is not. Is it limited by the availability of source compounds, hydrogen in particular? Active methanogens are observed.  
  
The thermodynamic data of the gas mixtures are poorly known. |  
| Chapter 7 | It is essential to obtain more data (gas contents, microbes, isotopic) from deep, saline groundwaters, and drillholes possibly deeper than the existing ones, but further away (i.e. not in the repository volume) may have to be considered. Gas data will be integrated with isotopic data of fracture calcites and pyrites, which will provide information on methane consumption and production. New gas data are also planned to be obtained from the matrix pore space. The gas phase is an uncertainty, which probably cannot be verified with current sampling methods. Modelling may help in understanding the accumulation of methane in the system and whether oversaturation is possible. Methane diffusion can be evaluated by studying helium gas evolution, which may give more information on the methane fraction from different sources and its rate of accumulation. |

### I14: Evolution of groundwater composition: Evidence of deep infiltration of dilute

| S1, S17, S18 | As assessed in Chapter 7, the infiltration of dilute waters, such as glacial meltwater or meteoric recharge to repository depths, seems improbable, according to groundwater and pore water data, although flow simulations may suggest this possibility. Glacial components are present in mixtures of more saline and |  
| Chapter 7 | The non-existence of previous diluted conditions and preserved anaerobic conditions should be further confirmed by palaeohydrogeological studies and |
waters

diluted waters. No signs of the existence of fresh waters at repository depths have been observed at Olkiluoto, at least not for the Quaternary period. Essentially all fractures are covered by fracture minerals and there is no evidence of the recent corrosion of these minerals. Pore water studies do not support any glacial water (dilute) penetration in the bedrock.

| I15: Evolution of groundwater composition: Potential for upconing of very saline water. | S1, S17, S18 | As shown in Chapter 9, all model calculations to date have indicated the potential for meeting higher than current salinities at repository depths. The degree of upconing will partly depend on the hydraulic connections to the saline water and the ONKALO. Given that it is a fracture system, the temporal evolution and exact locations of these intrusions will be very hard to predict in detail. It will be very hard to totally discard the possibility of intrusion of water with a higher salinity than the present value, despite engineering actions (e.g. grouting) made to mitigate the problem. Predicting upconing requires – besides the knowledge of spatial groundwater extraction rates and evolution of the water table – site-specific information about the hydrostructures, their properties (transmissivity and flow porosities), the location of the freshwater–saltwater interface, and the salinities of deep groundwaters. Groundwater samples are taken from locations of good yield, i.e. hydrogeologically well-connected locations, which | groundwater studies from poorly-transmissive fractures and from pore space. Calibration with the flow model will determine the potential for the penetration of deglaciation waters to great depths. The Littorina model will also be extended and tested to include the deglaciation phase. Palaeohydrogeological studies of fracture minerals and U-series measurements in fracture interfaces will give additional data from previous deglaciations. Further action can be done in investigating the locations of the ice margins from the latest glaciations and the related deposits, where hydrogeological conditions have been stable. | ONKALO impact is addressed in Chapter 9 (P/O studies). The issue is currently handled by monitoring during construction and taking actions (grouting etc.) if there are signs of upconing. Future updates of the hydrogeological/hydrogeochemical modelling, making use of the additional site data, may enhance the predictive capability. The drillhole beneath the sea (OL-KR47) may contribute considerably to our understanding of the past evolution of the saline interface and thereby help in a more definite evaluation of its future movement. More data from deep groundwaters would be helpful, although it is known that the observed salinities are quite high at |
means that the samples are mixtures of less and more saline waters than the original salinity at the sample point. Some understanding of the location of the interface has been developed: no sharp interface exists at the site scale, but there seems to a well-defined transition zone with a width of a couple of hundred metres. (Note that the literature on upconing usually concerns a more idealised situation, in which an (eventually) sharp steady-state saltwater interface is maintained below the "sink" (usually a drillhole) and the conditions that should be met so as to prevent the interface’s movement to the sink. In reality, and especially in a heterogeneous medium such as fractured rock, a sharp and steady interface is not to be expected). Olkiluoto. In principle, denser water (i.e. more saline water) is less prone to upconing. Numerical modelling is a good means of assessing the impact of uncertainties on the magnitude of this effect.

<table>
<thead>
<tr>
<th>Transport properties</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I16: Site evidence for flow related transport properties of migration paths from the potential repository panels.</strong></td>
<td>S7</td>
<td>Chapter 8</td>
</tr>
<tr>
<td></td>
<td>Direct site evidence on the migration properties in parts of the rock containing few and poorly-transmissive fractures is hard to obtain, and the properties have to be assessed via modelling. Compared to previous migration models (e.g. in TILA99, Vieno and Nordman 1999), the current migration modelling, based on the new hydrogeological DFN, is judged more realistic, as it aims to capture the spatial variability of the flow along migration paths, the retention properties along the migration paths, and their correlation. The properties used in this model are obtained directly from the site-specific data and from the other models of the Olkiluoto site. Several alternatives regarding e.g. fracture size, fracture frequency and correlation between size and transmissivity, see Chapter 8, are presented and assessed. Characterising the flow distribution is mainly related to the description of how the potentially-transmissive fractures form a connected network. The flow cannot be measured for future conditions, the flow path distribution has to be based on modelling, i.e. the hydrogeological DFN and estimates of the future boundary conditions. The question is then whether the hydrogeological DFN is</td>
<td></td>
</tr>
</tbody>
</table>
sufficiently bounded by the available hydrogeological data. This is the same issue as already discussed in issue I4, see above.

**I17 Site evidence for the retention properties of the rock from the potential repository panels.**

<table>
<thead>
<tr>
<th>S8</th>
<th>Data on retention properties are obtained from laboratory tests on core samples. A few such samples from Olkiluoto exist and have been analysed, but there is a question as to whether these samples are representative of the actual migration paths. There are samples from the HZs, but these contribute little to retention, even if they are important for the buffering of intruding waters. There are also samples from the less conductive parts of the rock mass, but coupling these to the migration paths in this rock can only be made using a statistical approach. This needs further development. Another issue worth consideration is whether long-term changes of the minerals on fractures and in the matrix, due to precipitation and dissolution, would imply that retention properties change over time. The great age of the fracture minerals suggests this is not an issue – but this has not been formally assessed yet. There may also be a bias on porosities measured in the laboratory, as these may possibly be affected by stress release. Only a limited number of sorption coefficients are obtained from in situ tests. The understanding of sorption, and its dependence on groundwater chemistry needs to be supplemented by generic data.</th>
</tr>
</thead>
</table>

**Chapter 8**

The current scarcity of data needs to be handled in order to enhance confidence. The following actions are needed:

- The further development of a statistical approach for judging the representativity of samples. Some information on this will come from the assessment of fracture mineralogy. Part of this assessment will be to consider whether there really are statistically different properties in different fractures or in different parts of the rock.
- An assessment as to whether retention properties change over time.
- An assessment of the potential biases due to stress release, e.g. by comparing with in situ methods such as electrical resistivity logs.
- Statistical representativity of the rock matrix retention properties will be supported by the characterisation programme planned for the rock below HZ20. The measuring...
### Programme will include

Characterisation of the drill cores in order to identify immobile retention zone properties, studies in the ONKALO of the in situ diffusivity and investigations of the sorption properties of the altered and unaltered rock matrix from core samples of the representative drillholes.

### Overall site understanding and predictability issues

<table>
<thead>
<tr>
<th>I20 Relation between pilot hole data and conditions in the excavated tunnel and its environment</th>
<th>Chapter 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>There is generally a good correlation between what has been seen in pilot holes and what is then encountered when mapping the excavated tunnel, but there are some discrepancies. The fracture frequencies measured on the pilot hole drill cores are currently measured as being higher than the frequencies mapped on the adjacent tunnel walls. It is still unclear whether this is due to the difference in the resolution of the mapping of the tunnel walls and the pilot hole core, or if the core contains artificial breaks. This generally raises the question about the reliability of the fracture mapping of any drill core. Predictions on rock mass stability and actual behaviour (i.e. instability events) or measures taken for reinforcement show some discrepancies. Pilot hole data generally show that the rock is between good and very good and this is also generally the case in the excavated tunnels. However, the pilot holes do not have sufficient information to allow the identification of isolated stability problems. The diameter of the pilot holes is too small to reveal the exact location of potential unstable rock blocks, even if the pilot hole data usually are sufficient to tell what type of rock</td>
<td>An effort is needed to further explore the reason for differences between the fracture frequency in pilot hole drillcores and the mapped fracture frequency on the tunnel walls. It may be considered sensible to remap a drill core section (e.g. discarding mapped fractures parallel to the foliation) and remapping a section of the tunnel wall at a high resolution and then compare the outcomes. A numerical analysis of the correlation between transmissive sections in closely-spaced pilot holes should be made with the hydrogeological DFN model. It would also be of interest if the number of &quot;inflow points&quot; in the tunnel and in the pilot holes could be compared, cf. discussion on issue I4.</td>
</tr>
</tbody>
</table>
Inflows to tunnels are disturbed by “skin effects” and grouting, making quantitative comparisons between pilot hole data and actual tunnel conditions difficult. In addition, fracture transmissivity varies within the plane of a fracture. However, some qualitative observations can be made. Usually, the pilot holes predict higher inflows than are actually observed, but there are several occasions where the pilot holes suggest dry conditions – but where it eventually was necessary to grout (based on probe hole data) or post-grout due to unacceptably high inflows. Closely placed pilot holes, i.e. in the shaft, showed quite different hydraulic condition. The inflow points for the high T fractures are essentially the same, whereas the low T fracture inflow points differ. Transmissivity values differ up to an order of magnitude between the pilot holes.

Water samples taken from the ONKALO appear similar to the water samples taken from the pilot holes. Samples taken from ONKALO also correspond well with field data, in general. However, pilot hole samples from sections of low transmissivity and high porosity, i.e. with hydraulic conditions deviating from those conditions from which data sampled outside the ONKALO were obtained, also deviate to a certain extent from the general trends (cf. issue I1). Such samples are e.g. found in ONK-PH2, ONK-PH6, ONK-PVA2.

<table>
<thead>
<tr>
<th>I21 What is the scale of natural variability of deformation zones?</th>
<th>S3</th>
<th>Chapter 4</th>
<th>Work is under way to characterise the variability of the influence zone of local deformation zones and this is very dependent on tunnel observations. The issue is important in order to assess the uncertainties within the modelling of local deformation zones and also, for the RSC programme when considering...</th>
</tr>
</thead>
<tbody>
<tr>
<td>The cores and influence zones, are established for the larger deformation zones (see Chapter 4) which show the variability of the properties of the zones in drillhole intersections. For site-scale zones, the core sections are usually from 10 cm to a metre in width, whereas the zones of influence are in the order of tens of metres. Tunnel observations also indicate that the intersected local deformation zones usually have a variability in the core thickness from a few cm to a few tens of cm.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Detailed hydrogeological characterisation of e.g. a niche, would give some further indication of the spatial heterogeneity of the flow system (see also issue I4)
| I22 Capability to predict spalling | S13 | Based on strength and stress estimates, it is possible to assess whether spalling is likely to occur. It seems that the few occasions of observed spalling in the ONKALO occurred at the expected tunnel orientations. The uncertainty in stress (see issue I6) and the spatial variability of rock strength (see issue I7) result in uncertainty regarding spalling predictions. In relation to the potential for spalling in the deposition holes, there is uncertainty in fully understanding and quantifying the importance of a counter pressure to suppress the spalling, even if it is clear that quite moderate counter pressures (in the order of 0.5-1 MPa or less) would be sufficient. | The basic data for making predictions of spalling are provided in Chapter 5, whereas Section 9.3 addresses the observed and potential spalling during construction of the ONKALO. Uncertainty will be reduced by reducing uncertainty in the magnitudes of the stress and the rock strength (see issues I6 and I7), but there is a spatial variability that data cannot be reduced. Scoping calculations, including the thermal evolution, on the importance of counter pressures to suppress the spalling will continue. Current SKB experiments in the Åspö HRL may also provide new insights in this area. |
| I23 Characterisation of the Excavation Damage Zone (EDZ) of the ONKALO tunnel system | S12 | Experience to date suggests that there is likely to be a more extensive EDZ in the tunnel floor. There are still only few, and difficult to interpret, hydraulic data on the EDZ and, although they suggest that the transmissivity of the EDZ is quite low, their interpretation is uncertain. Thus there are good reasons for trying to further characterise the EDZ. It needs also be realised that the EDZ's characteristics may be very different during the construction of the ONKALO, when the tunnel is open, from after the closure of the repository, when it has been backfilled and becomes resaturated. The hydrogeological literature terms this kind of EDZ as tunnel skin, which, actually contributes favourably to the tunnel's hydrogeological isolation from its surroundings when the tunnels are open; but which evolves into a potentially conductive hydrogeological feature after resaturation. | Chapter 9 | New EDZ holes and niche studies are planned in the ONKALO and plans for a hydraulic characterisation of the EDZ are being formulated. |
| I25: Impact of the open drillholes on the hydraulic connections of natural deformation zones | S1 | Multi-packers have now been installed in most drillholes that previously were open. This issue is not seen as a major concern any more. (Will not be included as an issue in future Site Reports, unless new information suggests this is necessary.) | Chapter 9 | Monitoring the recovery of these drillholes from their open stage will continue. |
| **I26: Existence of high pH plume and other impacts of grouting** | **S1, S15** | As further discussed in SR2006, fracture minerals (in addition to CO$_2$ in groundwater) are able to neutralise a high pH plume, although the kinetics of these processes are very uncertain. To date there are few indications of elevated pH from the groundwater sampling. At some points pH values above 8 are found, but these values are caused by natural processes, and need not be related to the grouting. The influence of grouting cement has also been monitored in drillhole experiments at shallow depth in the ONKALO. The results showed significant decrease in pH values over a few years, but the experiments were not hydrogeologically well controlled (Arenius et al. 2008). It should be also noted that the ONKALO is now approaching depths where the natural pH buffering capacity is lower. | **Discussed in SR2006 (Andersson et al. 2007).** | The monitoring of pH will continue. A well-controlled experiment could possibly provide further insights into whether a pH plume really develops. Reactive transport modelling exercises (e.g. as part of the Prediction/Outcome studies) to improve the understanding of the ability of local water-rock systems to neutralise high pH water may also be worthwhile. |
Appendix 10-3. Data support, confidence and uncertainty in the resulting SDM input to the safety case.

Table 10-1 shows how the Olkiluoto Site Descriptive Model is used in the Safety Case. Table 10-2 discusses the main remaining issues in deriving this site description. However, for traceability in the Safety Case it is also important to document the source of information in the SDM, the quality of this information and the resulting uncertainty and confidence. A summary table has been assembled covering:

- SDM property and how this is used as input to the Safety Case (make reference to Table 10-1)
- Characterisation data and other aspects supporting the estimate of the property (just a list with reference to the appropriate section in the main text)
- Have all available, relevant data/information been used for assessing this property?
- Is there poor accuracy, or pronounced bias in the information used to estimate the property? If so – what is nature and how has it been accounted for?
- Are there other sources of uncertainty in estimating the property? (e.g. low spatial coverage, poor process understanding, lack of useable site data…)
- Are uncertainties in the properties bounded – and with what confidence? Are there contradictory data that may even suggest the potential for alternative interpretation/models?
- What are the main reasons for this confidence (or lack of confidence)?
Table 10-3. Data support, confidence and uncertainty in the resulting SDM input to the Safety Case.

<table>
<thead>
<tr>
<th>SDM property and how this is used as input to the safety case (make reference to Table 10-1)</th>
<th>Type of characterisation data and other aspects supporting the estimate of the property (just a list with reference to appropriate section in the main text)</th>
<th>Is there any available, relevant data/information that not have been used for assessing this property?</th>
<th>Is there poor precision, or pronounced bias in the information used to estimate the property? If so – what and how has it been accounted for?</th>
<th>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of useable site data…)</th>
<th>Are uncertainties in the properties bounded – and with what confidence</th>
<th>Is there contradictory data that may even suggest potential for alternative interpretation/models</th>
<th>Are we confident, and if so what are the main reasons for this confidence (or lack of confidence)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geological</td>
<td>Lithological model (rock type distribution etc) in repository volume</td>
<td>Core logging, surface mapping, ONKALO tunnel data, petrophysical sampling and magnetic measurements, as well as on the understanding of geological history of the site, especially of the ductile deformation, which directly affects the lithological distribution.</td>
<td>The relationship between block faulting and lithological distribution has not been assessed and, if the displacement of the faults has been significant, this should be reflected in the lithological model. The lack of proper key markers makes this assessment difficult, but will nevertheless be considered in future work.</td>
<td>There is no bias at the site-scale, as the new drillholes seem, more or less, to confirm the results of earlier models.</td>
<td>In the eastern part of the island there is a low data coverage, but new drillholes will resolve this issue. The uncertainties in the understanding of ductile deformation are directly linked to the lithological model.</td>
<td>Uncertainties in the site-scale lithological model are considered to be bounded, as the key aspects controlling the lithological distribution are known and the data coverage is mainly good.</td>
<td>The confidence of the site-scale lithological model is considered as high in the well-investigated area, as shown by prediction-outcome work. Due to poorer data coverage, the confidence in the eastern area is lower.</td>
</tr>
<tr>
<td>SDM property and how this is used as input to the safety case (make reference to Table 10-1)</td>
<td>Type of characterisation data and other aspects supporting the estimate of the property (just a list with reference to appropriate section in the main text)</td>
<td>Is there any available, relevant data/information that not have been used for assessing this property?</td>
<td>Is there poor precision, or pronounced bias in the information used to estimate the property? If so – what and how has it been accounted for?</td>
<td>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of useable site data…)</td>
<td>Are uncertainties in the properties bounded – and with what confidence</td>
<td>Is there contradictory data that may even suggest potential for alternative interpretation/models</td>
<td>Are we confident, and if so what are the main reasons for this confidence (or lack of confidence)?</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Ductile deformation model (especially Foliation)</td>
<td>Core logging, surface mapping, ONKALO tunnel data, Magnetic measurements. Understanding of the ductile deformation history.</td>
<td>Data on the small-scale foliation have not yet been made use of as fully as might be, and the relationship between block faulting and the ductile deformation model has not yet been fully assessed, e.g. ductile kinematics, aging methods, and plate tectonics studies can probably be used more efficiently by suitable sampling of features of different deformation phases.</td>
<td>There is no bias at the site-scale, as new drillholes seem, more or less, to confirm the results of earlier models. However, the ductile deformation model is continuously developed as new data are acquired and, as a consequence, the precision of the model is also continuously increasing.</td>
<td>There is good data coverage in the site-scale model, but for the modelling of small-scale variation of, for example, folding and foliation, the site-scale coverage may not be sufficiently high.</td>
<td>Uncertainties in the site-scale ductile deformation model are considered to be bounded, as the site-scale understanding of the ductile deformation seems to be quite robust with respect to newly-acquired data. For small-scale variations, the uncertainties are not that well-bounded and further work is needed to assess the effect of such variations. This assessment should of course be linked to the needs of the end users of the data, i.e. what is the required resolution?</td>
<td>There is high level of confidence in the model, since it seems to explain the current observations.</td>
<td></td>
</tr>
<tr>
<td>SDM property and how this is used as input to the safety case (make reference to Table 10-1)</td>
<td>Type of characterisation data and other aspects supporting the estimate of the property (just a list with reference to appropriate section in the main text)</td>
<td>Is there any available, relevant data/information that have not been used for assessing this property?</td>
<td>Is there poor precision, or pronounced bias in the information used to estimate the property? If so – what and how has it been accounted for?</td>
<td>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of useable site data...)</td>
<td>Are uncertainties in the properties bounded – and with what confidence</td>
<td>Are there contradictory data that may even suggest potential for alternative interpretation/models?</td>
<td>Are we confident, and if so what are the main reasons for this confidence (or lack of confidence)?</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Spatial alteration model</td>
<td>Core logging, surface mapping, ONKALO tunnel data, Gamma-measurements. Understanding of the alteration processes.</td>
<td>The relationship between fracturing, faulting and alteration has been assessed in the current models, but this assessment should be further continued in order to increase the understanding of the alteration processes. The physico-chemical properties of the altered rock types are still under investigations and these data should be taken into account, when available.</td>
<td>There is no bias in the data and they are considered precise.</td>
<td>The low spatial coverage in the eastern area affects the confidence in the model in the eastern part of the island.</td>
<td>Currently the alteration model only accounts for the spatial distribution of pervasive alteration, whereas fracture-controlled alteration is also common. The current understanding of the spatial distribution of the pervasive alteration is considered to be fairly good, yet the degree and properties of the alteration, which are currently under investigation, may result in additional uncertainties to the current model. The currently-modelled volumes of pervasive alteration may contain more heterogeneous smaller volumes with respect to their physico-chemical properties. Once data on this factor have been obtained, their effect on the current model needs to be assessed.</td>
<td>The level of confidence in the model is judged to be high, since the new data obtained to date have more or less confirmed the results of the model. However, the issues stated above need to be taken into account in future modelling work.</td>
<td></td>
</tr>
<tr>
<td>SDM property and how this is used as input to the safety case (make reference to Table 10-1)</td>
<td>Type of characterisation data and other aspects supporting the estimate of the property (just a list with reference to appropriate section in the main text)</td>
<td>Is there any available, relevant data/information that have not been used for assessing this property?</td>
<td>Is there poor precision, or pronounced bias in the information used to estimate the property? If so – what and how has it been accounted for?</td>
<td>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of usable site data...)</td>
<td>Are uncertainties in the properties bounded – and with what confidence? Is there contradictory data that may even suggest potential for alternative interpretations/models?</td>
<td>Are we confident, and if so what are the main reasons for this confidence (or lack of confidence)?</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Deformation zones (S3)</td>
<td>mapping, ONKALO tunnel data, magnetic measurements, mise-à-la-masse measurements, VSP, 3D seismics and the understanding of the brittle deformation history. Modelled deformation zones outside the well characterised area are only based on seismic data and the understanding of the brittle deformation zone history.</td>
<td>further explored to obtain an understanding of the age relationship of various faults and the relationship of modelled local-scale faults and site-scale faults should be further assessed.</td>
<td>geometry potentially masks subvertical faults, yet the data density in the central part of the Island is high enough to reveal any site-scale subvertical faults and this bias is therefore related to local-scale faults.</td>
<td>scale faults outside the central part of the Island is a source of uncertainty. The extrapolation is based on some geophysical data, but also on expert judgment – direct control is lacking in these areas.</td>
<td>bounding lineaments is currently unknown, due to lack of data. Low spatial coverage of drillholes increases uncertainties in the eastern part of the Island</td>
<td>confidence in the geometry and extent of the site-scale faults within the central part of the Island, as demonstrated by the new data. The level of confidence regarding the extent and geometry of the site-scale faults in the eastern part is lower.</td>
<td></td>
</tr>
<tr>
<td>Fracturing Fracture description (S4)</td>
<td>Core logging, mapping of trenches and ONKALO mapping.</td>
<td>There is a good understanding of the fracture filling mineralogy, but no correlation with other fracture attributes. Further studies are needed to clarify the properties of typical fractures in the bedrock by combining e.g. geometry, mineralogy, and porosity profiles.</td>
<td>See next column</td>
<td>The DFN modelling is based on the mapped fractures in the drillholes and in the first tunnel sections of the rock volume. This and the potential for a better developed surface fracturing can cause biases in the fracturing models. This bias will be corrected when mapped tunnel data from greater depths become available.</td>
<td>There is uncertainty in the DFN models, indicated by different alternative DFN models, based on different weighting of the data. These models are predicting slightly different fracture patterns.</td>
<td>There is a basic level of confidence in the geological DFN model, since the fracture data collected from the tunnel and drillholes and from the surface mapping show the same general similarities.</td>
<td></td>
</tr>
<tr>
<td>SDM property and how this is used as input to the safety case (make reference to Table 10-1)</td>
<td>Type of characterisation data and other aspects supporting the estimate of the property (just a list with reference to appropriate section in the main text)</td>
<td>Is there any available, relevant data/information that have not been used for assessing this property?</td>
<td>Is there poor precision, or pronounced bias in the information used to estimate the property? Is so – what and how has it been accounted for?</td>
<td>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of useable site data...)</td>
<td>Are uncertainties in the properties bounded – and with what confidence? Is there contradictory data that may even suggest potential for alternative interpretation/models</td>
<td>Are we confident, and if so what are the main reasons for this confidence (or lack of confidence)?</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td><strong>Rock mechanics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Stress</strong> Stress state (S9)</td>
<td>In addition to the stress data existing before 2006, the stress model is based on shaft measurements, made in 2007 – 2008, OC measurements made in ONKALO and a semi-integrated stress analysis.</td>
<td>All the stress data have been considered, but data which are judged as inadequate have not been used in specifying the stress state.</td>
<td>Some test results have a low level of accuracy, but the stress estimates have been made using the more reliable data. All overcoring data from the ONKALO suffer from irregular consistency, most probably related to the high heterogeneity of the rock in respect to test size and the behaviour of the glue.</td>
<td>There is low spatial coverage (no data yet from eastern area) and there could be regions at the Okiluoto site where the stress field is different because of the influence of brittle deformation zones in deflecting the stresses.</td>
<td>The uncertainties are not well bounded and the range is large (cf. highest/lowest values – but need better estimates). Recent larger scale measurements in shafts indicate that the major principal stress may be N-S, rather than NW-SE, at least above HZ20. The magnitudes of the stresses are also on the upper boundary of the SR2006 estimate.</td>
<td>There is an overall confidence in the stress model, because of its consistency with the regional stress state in Fennoscandia, but there is less confidence in its details because of the potential for local deviations in the magnitudes and orientations of the principal stresses. The effect of the BDZs has not yet been studied, and such a study has been postponed to SR2010 because of the small number of reliable stress data for comparison.</td>
<td></td>
</tr>
<tr>
<td><strong>Intact rock properties</strong> Rock mechanics properties (S10)</td>
<td>Laboratory tests on rock core samples Point load and Schmidt hammer tests on site.</td>
<td>Correlation between different strength estimation methods will be done in early 2009, also checking the possible correlation with geological and geophysical mapping data.</td>
<td>The data are somewhat imprecise, because there is a large standard deviation due to the heterogeneity of the rock. However, this is typical and accounted for by using the full distribution of rock strengths in the analyses, e.g. in spalling analyses. The effects of</td>
<td>The data are unbiased.</td>
<td>The uncertainties in rock modulus and strength are bounded.</td>
<td>Confidence is achieved by using the full distributions of the various parameters. The possible use of geological and geophysical mapping information has not yet been fully investigated.</td>
<td></td>
</tr>
<tr>
<td>SDM property and how this is used as input to the safety case (make reference to Table 10.1)</td>
<td>Type of characterisation data and other aspects supporting the estimate of the property (just a list with reference to appropriate section in the main text)</td>
<td>Is there any available, relevant data/information that has not been used for assessing this property?</td>
<td>Is there poor precision, or pronounced bias in the information used to estimate the property? If so – what and how has it been accounted for?</td>
<td>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of useable site data...)?</td>
<td>Are uncertainties in the properties bounded – and with what confidence?</td>
<td>Is there contradictory data that may even suggest potential for alternative interpretation/models?</td>
<td>Are we confident, and if so what are the main reasons for this confidence (or lack of confidence)?</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Fractures</td>
<td>Q mapping data. Laboratory tests exist only for one of the three major types of fractures, but this will be completed in 2008/2009.</td>
<td>All data are considered.</td>
<td>Fracture property data are somewhat imprecise, due to the heterogeneity of the fracture surfaces.</td>
<td>There is no bias in the fracture property data. There is no bias in fracture orientations, but possibly a bias in fracture frequencies, as measured in the different mapping situations. However, this bias is understood and can be accounted for.</td>
<td>Uncertainties are bounded</td>
<td>There is no bias in fracture orientations, but possibly a bias in fracture frequencies, as measured in the different mapping situations. However, this bias is understood and can be accounted for.</td>
<td>There is a very high confidence in the fracture geometry for rock mechanics purposes, because of the wealth of mapping data on fractures. There is less confidence in the mechanical properties of fractures.</td>
</tr>
<tr>
<td>Potentially unstable rock blocks</td>
<td>To calculate rock mass properties</td>
<td>All data are considered.</td>
<td>Data are somewhat imprecise, due to the heterogeneity of the fracture zones.</td>
<td>There is low spatial coverage.</td>
<td>A very coarse bound of the uncertainty for strength is between zero and the intact rock strength.</td>
<td>Confidence in the values given is limited, since no relevant direct measurements have yet been made.</td>
<td></td>
</tr>
<tr>
<td>Deformation zone properties</td>
<td>Q mapping data where there are drillcore or tunnel intersections.</td>
<td>All data are considered</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

rock types, foliation and heterogeneity are a potential source of uncertainty, but this is accounted for by using the complete distribution of rock strengths. There is a need to clarify what this imprecision relates to: the method of testing or the location of the samples. Furthermore, the long-term strength and spalling strength data are not yet fully understood.
<table>
<thead>
<tr>
<th>SDM property and how this is used as input to the safety case (make reference to Table 10-1)</th>
<th>Type of characterisation data and other aspects supporting the estimate of the property (just a list with reference to appropriate section in the main text)</th>
<th>Is there any available, relevant data/information that have not been used for assessing this property?</th>
<th>Is there poor precision, or pronounced bias in the information used to estimate the property? If so – what and how has it been accounted for?</th>
<th>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of useable site data...)</th>
<th>Are uncertainties in the properties bounded – and with what confidence</th>
<th>Is there contradictory data that may even suggest potential for alternative interpretation/models</th>
<th>Are we confident, and if so what are the main reasons for this confidence (or lack of confidence)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation zones</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock mass properties</td>
<td>Data are evaluated from intact rock and fracture properties.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elastic modulus and failure characteristics of the rock mass</td>
<td>Information on in situ strength (tunnel scale) has not yet been studied and the currently used estimates are based on information for homogeneous rock types (at the URL in Canada, and at the Åspö HRL in Sweden). Tests on ONKALO rock types are being planned.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity and</td>
<td>Laboratory measurements from All data are used</td>
<td>The data have high precision but show a large</td>
<td>The data have no bias, but the spatial coverage is low.</td>
<td>The uncertainty is bounded. The lower end and the</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Confidence is based on the ability to make sufficient empirical estimates based on the large amount of mapping data available from the drillholes, pilot holes and tunnel mapping.
<table>
<thead>
<tr>
<th>SDM property and how this is used as input to the safety case (make reference to Table 10-1)</th>
<th>Type of characterisation data and other aspects supporting the estimate of the property (just a list with reference to appropriate section in the main text)</th>
<th>Is there any available, relevant data/information that not have been used for assessing this property?</th>
<th>Is there poor precision, or pronounced bias in the information used to estimate the property? If so – what and how has it been accounted for?</th>
<th>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of useable site data…)?</th>
<th>Are uncertainties in the properties bounded – and with what confidence</th>
<th>Is there contradictory data that may even suggest potential for alternative interpretation/models</th>
<th>Are we confident, and if so what are the main reasons for this confidence (or lack of confidence)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>heat capacity</td>
<td>drillcores and some preliminary in situ measurements with the TERO probe, as further discussed in Chapter 5.</td>
<td>variation, which is due to the heterogeneity of the rocks at Olkiluoto.</td>
<td>The effect of rock types, foliation, heterogeneity and upscaling is a potential source of uncertainty.</td>
<td>anisotropy of the thermal conductivity distribution are well bounded. More tests are needed to define thermal expansion properties.</td>
<td>which are well supported by the geological descriptions, where the anisotropy is related to the occurrence of mica, whereas the spatial variability is essentially at a very local scale and averages out at larger scales. The TERO probe data suggest that the upscaling does not overestimate the thermal conductivity. However, very few in situ data exist today to understand the thermal properties at larger scales (i.e. the deposition hole scale).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In situ temperature</td>
<td>Temperature logging in drillholes</td>
<td>All data are used.</td>
<td>No.</td>
<td>No.</td>
<td>Yes</td>
<td>High confidence</td>
<td></td>
</tr>
<tr>
<td>Hydrogeology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### SDM property and how this is used as input to the safety case (make reference to Table 10-1)

<table>
<thead>
<tr>
<th>Type of characterisation data and other aspects supporting the estimate of the property (just a list with reference to appropriate section in the main text)</th>
<th>Is there any available, relevant data/information that have not been used for assessing this property?</th>
<th>Is there poor precision, or pronounced bias in the information used to estimate the property? If so – what and how has it been accounted for?</th>
<th>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of useable site data…)</th>
<th>Are uncertainties in the properties bounded – and with what confidence</th>
<th>Are there contradictory data that may even suggest potential for alternative interpretation/models</th>
<th>Are we confident, and if so what are the main reasons for this confidence (or lack of confidence)?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydraulic Zones Deformation zone properties (S3)</strong></td>
<td>The geological BFZ model (including the model for lineaments); PFL observations for high transmissivities; responses to field activities, such as boring new drillholes; pumping tests; and recoded episodes of high ONKALO inflow water rates.</td>
<td>All data are used</td>
<td>Data are considered precise and unbiased, at least in the central part of the Island. &quot;Precision&quot; is intimately connected to the scale of the model (and this basically is determined by knowledge from the drillholes). Whilst some bias may be associated with the drillhole observations, as the dominant orientation of the drillholes is close to the vertical, the supporting (geological) information implies a gently-dipping, if not sub-horizontal, dominant fabric within the bedrock; making it amenable to investigations with high angle drillholes.</td>
<td>Outside the central part of the Island, the description of the hydrogeological zones is clearly more inaccurate, but this has limited impact on the flow in the central part of the Island.</td>
<td>Uncertainties are related to the continuation of some of the hydrogeological zones beyond the central part of the Island. Also some alternative interpretations are described in Chapter 6.</td>
<td>There is a very high confidence in the location and average hydraulic properties of the hydraulic zones in the central part of the Island. The existence and description of HZ19 and HZ20 is consistent with all hydraulic data and is also consistent with the geological model. There is less confidence in the location and properties of the potential vertical hydraulic zones, but the fact that very few such zones are found suggests there are very few. It may be different in the eastern area – there more data are needed before any conclusions can be drawn.</td>
</tr>
<tr>
<td><strong>Hydraulic properties of the rock volumes between HZs (HydroDFN model)</strong></td>
<td>The geological DFN and PFL measurements, and the division into fracture domains above and below HZ20. Pilot hole and ONKALO data could be used more for calibration and testing of the hydrogeological DFN model in future.</td>
<td>There are many representative data from the central part of the Island, but few from the eastern area. Also, the intensity of PFL data is low below approximately 400 m depth.</td>
<td>The uncertainty in the hydrogeological DFN model concerning fracture size and frequency is handled using different alternatives. It is judged that the range of these alternatives bounds</td>
<td>The hydrogeological DFN model, with its alternatives, reflects the measured PFL data. This means that there is high level of confidence in the central part of the Island, but less confidence outside</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDM property and how this is used as input to the safety case (make reference to Table 10-1)</td>
<td>Type of characterisation data and other aspects supporting the estimate of the property (just a list with reference to appropriate section in the main text)</td>
<td>Is there any available, relevant data/information that not have been used for assessing this property?</td>
<td>Is there poor precision, or pronounced bias in the information used to estimate the property? If so – what and how has it been accounted for?</td>
<td>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of useable site data...)</td>
<td>Are uncertainties in the properties bounded – and with what confidence?</td>
<td>Is there contradictory data that may even suggest potential for alternative interpretation/models?</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>to:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Fracture descriptions (S4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Groundwater flow (S5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Flow related migration properties (S7)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Flow model in site scale</strong></td>
<td><strong>EPM (S5)</strong></td>
<td>A great body of hydrogeological data (PFL/HTU transmissivities, responses to various field activities, pumping tests); it is also reconciled with the geological brittle deformation zone model.</td>
<td>All data are used</td>
<td>Some bias may arise from the fact that rather few actual observations are available from the uppermost 50 m of the bedrock, as most of the deep drillholes have been equipped with surface casing.</td>
<td>There are few hydraulic data outside the central part of the island.</td>
<td>Uncertainties are similar to those in the Hydraulic Zone (HZ) model: outside the central part of the Island the undetected, and thus unknown, local structures are taken into account in the hydraulic conductivity of the sparsely fractured rock. The uncertainties are bounded to some extent with sensitivity and uncertainty analyses.</td>
</tr>
<tr>
<td>SDM property and how this is used as input to the safety case (make reference to Table 10-1)</td>
<td>Type of characterisation data and other aspects supporting the estimate of the property (just a list with reference to appropriate section in the main text)</td>
<td>Is there any available, relevant data/information that not have been used for assessing this property?</td>
<td>Is there poor precision, or pronounced bias in the information used to estimate the property? If so – what and how has it been accounted for?</td>
<td>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of useable site data...)</td>
<td>Are uncertainties in the properties bounded – and with what confidence</td>
<td>Is there contradictory data that may even suggest potential for alternative interpretation/models</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Boundary conditions</td>
<td>Water elevations in a large number of standpipes and on seawater salinity on the top surface of the model. The boundary conditions on the other boundaries (lateral and bottom) have been assumed without any direct observational data.</td>
<td>All data are used</td>
<td>For the present day situation, the uncertainties of the boundary conditions on the top of the model are generally small. In places, however, the uncertainty may be noticeable; especially in cases where a highly transmissive zone runs though an area of elevated terrain. One such a zone is HZ004. Moreover, whilst the uncertainties in the present day boundary conditions (water table, seawater salinity) are usually small, they are greater for the periods in the past, due to the general lack of direct information, e.g. on past shoreline.</td>
<td>The salinity of the Littorina Sea has been inferred indirectly. Similar uncertainties are associated with the initial state of the salinity field, whereas the uncertainty in the initial state of the water pressure for the submerged island at 8000 years ago is considered to be small.</td>
<td>On the top of the model the pressure boundary conditions (the water table) is bounded by the topography; the boundary condition for the salinity is bounded by the seawater salinity and the fresh water (i.e. zero) salinity.</td>
<td>The presence of the sea makes the general boundary conditions well known and well defined. On land there is quite a large number of hydraulic head data, resulting in a well-defined water table. With regard to the initial state, the greatest uncertainties are associated with the salinity field. At depth the salinity distribution is well known – and bounding estimates could be made – though, at shallow depths, this is more difficult, due to the strong spatial variability of permeability (see also issue I15).</td>
</tr>
</tbody>
</table>

explain the existing data.
<p>| Hydrogeochemistry | Groundwater samples with gas data, matrix pore water data, isotopic data and fracture EC data, as described in Chapter 7. | All data are used | Low permeable fractures are poorly characterised, but the number of data is increasing as a result of the ONKALO investigations and the pore water studies. Substantial differences exist between the pore water and the water sampled from fractures, regardless of the transmissivity of the sampled fractures; an effect which may be partly due to measurement bias. | The near-field groundwater compositions will depend on the hydrogeological conditions and the disturbance caused by the repository. The original conditions within HZ20A are uncertain, due to the influence of open drillholes and, therefore, it is difficult to estimate its real hydrogeochemical significance. However, salinity simulations with flow modelling do not indicate any outstandingly fast infiltration paths. | The groundwater composition varies slightly according to the hydrogeological properties of the host rock (low permeable vs. highly transmissive, older vs. younger), but this is controlled by the observed range of groundwater compositions and types. The lower salinities seen in pore water data suggest a different evolution of the salinity compared to groundwater samples or salinity simulations. The issue will be discussed in SR2010, after more data from low transmissivity fractures and matrix pore waters have been obtained. The current level of the hydrogeological model (i.e. the uncertainties regarding its details) does not provide the necessary level of detail. Nevertheless, we are generally confident in the distribution of water types and the increasing levels of data have not revealed any significant surprises. However, matrix pore water data from rocks at depth generally show more dilute water than in the permeable system; and the pore waters also appear to be very old. The origin of these dilute waters is uncertain, but their presence suggests a very low rate of exchange between the deep and near-surface groundwaters. |</p>
<table>
<thead>
<tr>
<th>SDM property and how this is used as input to the safety case (make reference to Table 10-1)</th>
<th>Type of characterisation data and other aspects supporting the estimate of the property (just a list with reference to appropriate section in the main text)</th>
<th>Is there any available, relevant data/information that not have been used for assessing this property?</th>
<th>Is there poor precision, or pronounced bias in the information used to estimate the property? If so – what and how has it been accounted for?</th>
<th>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of useable site data...)</th>
<th>Are uncertainties in the properties bounded – and with what confidence</th>
<th>Are there contradictory data that may even suggest potential for alternative interpretation/models</th>
<th>Are we confident, and if so what are the main reasons for this confidence (or lack of confidence)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Processes in the large scale, e.g. Sulphate reduction, redox, control of divalent cations, gas. This is input to assessing groundwater composition in the near-field (S1)</td>
<td>Groundwater samples, isotopic data, microbial data, dissolved gas data, fracture mineral mapping, analyses of mineral compositions, palaeohydrogeological studies of fracture mineralogy, isotopic studies of fracture minerals, fluid inclusions, information from other sites (analogy studies) and thermodynamic constraints.</td>
<td>The use of distributional fracture mineral analyses (based on chemical and isotopic data) to describe hydrogeochemical processes may give more detailed information at the local scale.</td>
<td>See next column</td>
<td>Potentially poor representativity may imply some bias. Different data describe different volume scales of the bedrock. Mineralogical studies have been sporadic and potentially important information may have been lost due to the resulting limited volumetric representativity. Different data may represent different time episodes, thus integrated interpretations may be misleading particularly when older episodes (i.e. preglacial) are evaluated. Detailed mineralogical studies of the latest fracture precipitates and pore water studies, together with sampling from low transmissive features, may produce a more coherent picture of ancient episodes, including also.</td>
<td>Ancient episodes are not fully represented in the different databases (groundwater, fracture minerals, alteration).</td>
<td>There is a fair level of confidence in recent processes since the Weichselian glaciation. Confidence is enhanced by the general understanding of hydrogeochemical processes, geochemical reactions are universal, and by the evidence that the palaeohydrogeological evolution is well understood. The sequence of older episodes is undefined and such episodes may also include unidentified processes.</td>
<td></td>
</tr>
<tr>
<td>SDM property and property of interest</td>
<td>Migration</td>
<td>Matrix properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------------</td>
<td>-----------</td>
<td>-------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of characterisation data and other aspects supporting the property (just a list)</td>
<td>Flow related migration properties: (ST)</td>
<td>The geological conceptualisation and definition of the matrix properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Are there other sources of uncertainty in the property (e.g. low spatial coverage, poor process understanding, lack of usable site data etc.)</td>
<td>Flowlogging of the shaft boreholes has not yet been used for transport modelling. These data could be used to assess the heterogeneity of the DFN and subsequently the statistical characteristics of the fracture transmissivities could be estimated. An estimate for the lower bound of the range of fracture transmissivities is 0.001 m/d and is based on the PFL detection limit.</td>
<td>The data on the lower bound of the transport resistance are based on the PFL, the PFL detection limit. The confidence that the models can be calibrated to the relevant data is high. Nevertheless, there are uncertainties in the model. The fracture transmissivities used in the model are estimated when flow paths are conditioned to, for example, certain flow rates. The nature of the transport resistance is so close to what is actually measured by the PFL, that confidence that the models can be calibrated to the available data is high. Nevertheless, there are uncertainties in the models. The fracture transmissivities used in the model are estimated when flow paths are conditioned to, for example, certain flow rates.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Are there uncertainties bounded – and with what confidence – the information used to estimate the property?</td>
<td>An estimate for of the lower bound of the fracture transmissivities is 0.001 m/d and is based on the PFL detection limit. This means that fracture transmissivities below the PFL detection limit (and potentially waterconducting) are not accounted for in the model.</td>
<td>An estimate for of the lower bound of the fracture transmissivities is 0.001 m/d and is based on the PFL detection limit. This means that fracture transmissivities below the PFL detection limit (and potentially waterconducting) are not accounted for in the model.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Are there any available, relevant data/information that have not been used for assessing this property?</td>
<td>The present hydrogeological DFN model is based on borehole data from the central part of the Island. This means that fracture statistics from the eastern part of the Island are not well sampled.</td>
<td>The present hydrogeological DFN model is based on borehole data from the central part of the Island. This means that fracture statistics from the eastern part of the Island are not well sampled.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Are there any available, relevant data/information that not have been used for assessing this property?</td>
<td>The hydraulic properties of the hydrogeological DFN model at the lower end of the range of fracture transmissivities could be affected by the detectability of the PFL device. Also, the connectivity of the hydrogeological DFN depends on the ratio of open (potentially water-conducting) to flowing fractures.</td>
<td>The hydraulic properties of the hydrogeological DFN model at the lower end of the range of fracture transmissivities could be affected by the detectability of the PFL device. Also, the connectivity of the hydrogeological DFN depends on the ratio of open (potentially water-conducting) to flowing fractures.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Are we confident, and if so what are the main reasons for this confidence (or lack of confidence)?</td>
<td>Uncertainties related to the structure of the hydrogeological DFN are handled by alternative models.</td>
<td>The fact that only limited matrix data are available reduces confidence in the lower bound of the transport resistance.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is there poor precision, or pronounced bias in the information used to estimate the property?</td>
<td>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of usable site data etc.)</td>
<td>Cogent arguments can be presented for defining the lower bound of the transport resistance.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Are there contradictory data that may even suggest alternative interpretations of the property?</td>
<td>Are there any available, relevant data/information that have not been used for assessing this property?</td>
<td>The geological conceptualisation and definition of the matrix properties are inherently quite uncertain because of the way the model is constrained.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDM property and how this is used as input to the safety case (make reference to Table 10-1)</td>
<td>Type of characterisation data and other aspects supporting the estimate of the property (just a list with reference to appropriate section in the main text)</td>
<td>Is there any available, relevant data/information that not have been used for assessing this property?</td>
<td>Is there poor precision, or pronounced bias in the information used to estimate the property? If so – what and how has it been accounted for?</td>
<td>Are there other sources of uncertainty in estimating the property (e.g. low spatial coverage, poor process understanding, lack of useable site data...)</td>
<td>Are uncertainties in the properties bounded – and with what confidence</td>
<td>Is there contradictory data that may even suggest potential for alternative interpretation/models</td>
<td>Are we confident, and if so what are the main reasons for this confidence (or lack of confidence)?</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Matrix related migration properties: (S8)</td>
<td>immobile zone, see Chapter 8, which in turn are based on core samples taken from OL-KR12 for the porosity and diffusion studies, and from OL-KR38 and OL-KR39 for the investigation of porosity and pore structure by PMMA method. No sorption data are assessed in this report.</td>
<td>migration properties. It is possible that the properties of all the immobile zones of the retention models cannot be directly measured; and they need to be based on concepts such as the dependence of the diffusivity on the porosity (Archie’s Law). Sorption properties for some of the immobile zones need to be estimated based, for example, on cation exchange capacity.</td>
<td>significant heterogeneity of and variability between hydraulic features. An in situ measurement programme will be initiated in order to collect appropriate migration data. There is uncertainty as to whether laboratory data are biased compared to in situ data. The means of bounding this uncertainty are being explored (see issue I17).</td>
<td>However, data can be compared with relevant information from other sites, for example SKB data.</td>
<td>diffusivity.</td>
<td>matrix-related retention properties. In general, matrix data from different sites, e.g. the SKB sites, tend to show rather similar values of formation factor and sorption properties. This could suggest that the fact that there are few matrix data from Olkiluoto is of a less concern, at least for justifying the lower bound values. Current models simplify the spatial variability and limit the differences between fractures. There are still too few site-specific data on the matrix properties.</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 10-4. Alternatives.

For each discipline Table 10-4:

- lists alternatives considered in SR2008
- discusses whether there are (or is a need for) additional alternative hypotheses (possibly allow a better differentiation between different conceptualisations, i.e. different models and the resolution/data uncertainty issues, see comments highlighting this below).

Table 10-4. Alternatives and potential alternative hypotheses.

<table>
<thead>
<tr>
<th>Discipline</th>
<th>Alternatives in Site Model 2008</th>
<th>Are there any other potential alternative hypotheses?</th>
</tr>
</thead>
</table>
| Geology          | No The confidence in the central part of the island is now quite high. There are three alternatives in the geological DFN model, depending on which input data are given the highest weight, see Chapter 4. | It is judged more meaningful to wait for new data, than to formulate different alternative model prematurely to handle the uncertainty in the eastern part of the island:  
  - There is a need to update the model for the eastern area once there are the necessary data. The deformation zone model in the eastern area is still unclear, since the faulting system appears to be different in some respects compared with the central part of the island. There appear, for example, to be more vertical features in the east.  
  - Currently the DFN model, which is based on data from the central part of the island, is just extrapolated to the east, but it is clear that the DFN model needs to be updated with data from the east, especially since the fracturing may be different there.  
  The geological DFN considers whether a fracture occurrence is correlated or clustered, but suggests that there is little evidence for this – apart from the need to divide the volume into two domains (A and B). |
| Rock Mechanics   | No, but there are few data from the eastern area.                                                                                                          | There are no alternative models, but it is noted that also in the central part of the Island the stress orientation and magnitude are uncertain. |
| Hydrogeology | The uncertainty being expressed by having wide bounds.  
| | - Within the precision of the stress data it is possible that the orientation of the major principal stress changes with depth.
| | - A more detailed stress model is anticipated, following numerical stress modelling and the evaluation of reliable stress data measured from the ONKALO below HZ20.
| Hydrogeochemistry | Whilst not true alternatives, there is a need to update the model once there are the necessary data. It should also be noted that the Åspö Task Force is modelling various pumping tests performed at Olkiluoto, and in the process applying different interpretations of the site hydrogeology. The findings of these studies were not available at the time of the completion of this report. | There are no main alternatives to the hydrostructure model in the central part of the island, since there is considerable confidence in the model in this area. However, there are alternative interpretations for some detailed structures, see Chapter 6. There is more uncertainty outside the central part of the island.
| | Both equivalent porous medium (EPM) and discrete fracture network (DFN) models have been derived. These are conceptually different descriptions of the hydraulic properties, but are judged to be consistent, i.e. their apparent differences are more a matter of scale and resolution.
| | The uncertainty in the hydrogeological DFN concerning fracture size and frequency is handled using different alternatives.
| Hydrogeochemistry | There is no alternative hydrogeochemical model, but there is uncertainty in the importance and/or strength of the different hydrogeochemical processes operating. However, uncertainties have decreased due to the large number of isotope data, which have clarified the processes operating at shallow depths during infiltration. | Some, not yet fully explored hypotheses, concern the origin and past distribution of the saline groundwater. The diluting water component in saline groundwaters could be the result of several ice ages and periods of warm climate. The infiltration of dilute meteoric groundwater may also have taken place to greater depth than that suggested from the distribution of current groundwaters. The overall process regarding the reduction of sulphide is understood, although the rate, kinetics and constraints on the process are less well known. |
| Transport | The uncertainty in the hydrogeological DFN connectivity is handled by different alternatives on fracture size and frequency, and by different alternatives on the correlation between transmissivity and fracture size. | There is uncertainty in the internal correlation structure between fractures, that would affect the connectivity of the fracture network. However, the hydrogeological DFN is calibrated against the PFL data (that actually measures connectivity) and it is judged that remaining uncertainties are covered by the different presented alternatives. It is known that fractures are internally heterogeneous and sensitivity analyses are used to bound the importance of this effect. There is still an issue as to how to derive the effective properties of the network. The influence of the heterogeneity on flow has been studied using flow logging data from the shaft boreholes. In parallel with this, flow-related retention properties under PA flow conditions in heterogeneous fractures are explored using modelling studies. These studies aim to develop a methodology for relating the effective flow and the description of the retention properties in a consistent manner for heterogeneous fractures. |
Appendix 10-5. Interactions between disciplines.

Another prerequisite for confidence is consistency (i.e. no conflicts) between the different discipline model interpretations. A protocol has been developed using an interdisciplinary interaction matrix for documentation, Table 10-5. For each interaction, the following questions have been addressed.

- Which aspects of the “source” discipline would it be valuable to consider in developing the “target” SDM?
- Which aspects of the “source” discipline have actually been used when developing the “target” SDM?
- Are there any discrepancies between answers to the first and second question, and if so why?

Discrepancies between what it would be valuable to consider and what actually is considered affects the confidence in the model. Again, it is primarily for the users to determine whether these discrepancies are significant or acceptable. However, an overview of this issue is provided at the conclusion of this section. In addressing the questions, the effort is spent primarily on issues judged to be important and not in explaining why unimportant interactions are indeed so.
**Table 10-5.** Interactions judged to be important (green) and to what extent these were actually considered (black). (There is a clockwise interaction convention in the matrix, e.g. influence of geology on rock mechanics is located in Box 1,2, whereas the influence of rock mechanics on geology is located in Box 2,1.)

<p>| Bedrock Geology | Deformation zone model, lithological model, DFN model, alteration model are input to the RM model. These inputs are used in the rock mechanics model. The P/O studies in particular rely heavily on the geological mapping and the results of the geological P/O studies. Geological domains were considered, but it was concluded that the differences between the lithological domains have little mechanical significance. | Lithological model, alteration, foliation is input to the thermal property model. The upscaling is a function of lithology. Is actually considered although there is still a lack of thermal property data from the altered rock. | Ductile deformation model, Deformation zone (DZ) model and DFN model are input to the hydrogeological model. Hydraulic properties could possibly also be correlated with the Lithological model. Correlation between DZ and hydraulic data is assessed (Chapter 6) and the models are consistent. DFN model is used for upscaling the drillhole hydraulic data and to develop a hydroDFN model. | Mineralogy of rock types and fractures, lithology and bedrock structure, bulk and mineral geochemistry, isotopic compositions and fluid inclusion data. Is actually considered (also DZs are considered when explaining the data). | Mineralogy of rock types and fractures should be used as input to the migration properties. The migration model considers the classification of different type fractures and the description of the non-conductive parts. |
| Stress model could give feedback on the mechanical character of deformation zone. Such feedback was not available for the Geological model (would require 3D stress modelling or new stress data). | Rock Mechanics (in the bedrock) | Stress affects thermal properties (minor effect). Has not been considered, impact much smaller than other uncertainties. | Change in stress can alter fracture hydraulic conductivity. Consider connection between stress orientation and potential anisotropy of hydraulic properties. The hydrogeological model is based on direct observations of hydraulic properties. The oriented PFL data are compared to the stress field. Coupling is one reason for the skin introduced in P/O inflow calculations (see Chapter 9). | No, although chemical activity could possibly be higher in regions of high stress. Potentially there is a relation between secondary fluid inclusions and the palaeo-stress field. Not being considered in current model. | Stress release on cores could bias laboratory tests. This is realised but not yet formally analysed. |
| Feedback on importance and required resolution in describing lithological domains, existence of alteration, intensity of foliation would affect level of ambition in the modelling. | Altered stress state due to thermal expansion Has been initially evaluated but will be further done in more detail? Important when assessing impact of the ONKALO and repository design, especially for long term stability (spalling). | Thermal (in the bedrock) Thermal buoyancy, but only potentially important during repository evolution phase – not for the descriptive model Not considered in the descriptive model. (Considered in the evolution modelling, cf. the Evolution Report). | Could potentially help in understanding of mineral activity in water-rock interaction. Not yet considered in detail, and coupling is probably weak. | Transport processes (dissolution/predipitation and retention) have some temperature dependence. However, the releases are expected to occur in the far future, when the impact of heat generated by the waste is negligible. |
| Feedback on existence and continuation of deformation zone model, validity of fracture data (system, intensity, size) and in general on the understanding of the brittle system. (It should also be noted that the geological model does not consider the hydraulic properties of the rock. Correlation between hydrogeological zones and geological model is being assessed (see Chapter 6). The hydrogeological zones can be geologically understood and the differences between the geological zones and the hydrogeological zones adds to the understanding of the nature of the brittle system. | Water pressure affects the stress state through the effective stress concept. Not taken into account but can be taken into effect in numerical programs. | No, heat transport is mainly by thermal conduction | Hydrogeology in the bedrock Analysis of potential flow paths between groundwater samples, hydrogeological conditions in drillholes as an evaluation tool of groundwater samples. Large scale groundwater simulations provide confidence in the hypotheses on origin and mixing processes of the various water types now found at the site. Is considered, see Chapter 6. | The flow related transport properties depend on the flow and the flow paths HydroDFN model is used as the key input for determining flow paths and assessing flow related migration properties. |
| There is a link through palaeohydrogeology, which aims to explain current fracture mineralogy. This could help explaining the age of the fractures. This is discussed in the hydrogeochemical chapter, but | Precipitation/dissolution in fracture alters the mechanical properties of the fractures. Could be a factor in long-term consideration of repository structural integrity. Not currently taken into account. | No | Salinity affects density and viscosity and thus the flow. Large scale groundwater simulations provide confidence in the hypotheses on origin and mixing processes of the various water types now found at the site. | Hydrogeochemistry (including microbiology) in the bedrock Groundwater composition affects migration properties. Is considered |</p>
<table>
<thead>
<tr>
<th>No direct link</th>
<th>No direct link</th>
<th>No direct link</th>
</tr>
</thead>
</table>

Migration properties derived should be consistent with the migration properties used in large scale simulations of groundwater flow and evolution ("the Littorina studies").

Has not been checked in SR2008 - should be done in SR2010.

The explanation of the mobile and immobile zone groundwater composition should be consistent with migration model.

Diffusivities estimated from the matrix pore water samples are presented in Chapter 7. They are reasonable in comparison to the diffusivities derived in the migration model.
Appendix 10-6. Changes since previous model version.

A final evaluation of the level of confidence concerns changes since the previous model version, i.e. since Site Report 2006. This is important for discussing the potential benefit of additional measurements. Clearly, if new data compare well with a previous prediction, the need for yet additional data may be limited.

A protocol has been developed for checking this, Table 10-6. It concerns:

- changes compared with the previous model version (i.e. Site Report 2006, Andersson et al. 2007),
- whether there were any “surprises” associated with these changes, and
- whether changes are significant or only concern details, i.e. is the model “stabilising”?

Table 10-6. Comparison with previous model version.

<table>
<thead>
<tr>
<th>List changes compared to previous model version (i.e. Site Report 2006)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geology</strong></td>
</tr>
<tr>
<td>An expansion of the modelled area to the east.</td>
</tr>
<tr>
<td>The geological model has been revised according to new data</td>
</tr>
<tr>
<td>and interpretations. The lineament interpretation was revised</td>
</tr>
<tr>
<td>and the results applied in the modelling work – the revision</td>
</tr>
<tr>
<td>was based to a considerable extent on magnetic data, which</td>
</tr>
<tr>
<td>seems to be the best indicator of the geometry of the brittle</td>
</tr>
<tr>
<td>deformation zones. New 3D seismic data were incorporated</td>
</tr>
<tr>
<td>within the model and a first model for the eastern part of</td>
</tr>
<tr>
<td>the Island is provided. Site-scale brittle deformation zones</td>
</tr>
<tr>
<td>are extrapolated to surrounding regional lineaments, if not</td>
</tr>
<tr>
<td>prohibited by direct observations. The alteration model is</td>
</tr>
<tr>
<td>revised, showing a clear correspondence of illitisation and</td>
</tr>
<tr>
<td>site-scale fault zones.</td>
</tr>
<tr>
<td>A first account of the development of the brittle deformation</td>
</tr>
<tr>
<td>history of the site is provided.</td>
</tr>
<tr>
<td>The development of a new geological DFN model.</td>
</tr>
</tbody>
</table>

| **Rock Mechanics**                                           |
| A new stress state model and fracture and fracture zone      |
| properties are now presented. More rock mechanics data (e.g. |
| rock response data) from the ONKALO are available.           |
| The development of a new geological DFN model.                |

| **Hydrogeology**                                             |
| The development of hydrogeological DFN model.                |
| An updated site scale (EPM) flow model has been developed.   |

| **Hydrogeochemistry**                                        |
| There has been an improvement in the understanding of        |
| groundwater composition under poorly transmissive conditions.|
| The importance of organics on groundwater compositions in    |
| recently-infiltrated groundwaters has been clarified, due    |
| to the availability of many more isotopic and microbial data.|

| **Transport**                                                |
| The inclusion of transport properties in the Site Report.    |
### Address whether there were any “surprises” connected to these changes

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology</td>
<td>No significant surprises</td>
</tr>
<tr>
<td>Rock Mechanics</td>
<td>Changes are not significant.</td>
</tr>
<tr>
<td>Hydrogeology</td>
<td>No</td>
</tr>
<tr>
<td>Hydrogeochemistry</td>
<td>SO\textsubscript{4} production from organic matter seems to be larger in shallow groundwaters than was expected. However, the significance of organic derived SO\textsubscript{4} in deep groundwaters is minor.</td>
</tr>
<tr>
<td>Transport</td>
<td>-</td>
</tr>
</tbody>
</table>

### Address whether changes are significant or only concern details – is the model stabilising?

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology</td>
<td>No – model is stabilising.</td>
</tr>
<tr>
<td>Rock Mechanics</td>
<td>Concerns details only</td>
</tr>
<tr>
<td>Hydrogeology</td>
<td>Concerns details only</td>
</tr>
<tr>
<td>Hydrogeochemistry</td>
<td>Variation of groundwater types with depth and transmissivities corresponds with general assumptions. Biologically-derived dissolved species explain previous uncertainties in geochemical processes - so the changes improve the logical base of the model.</td>
</tr>
<tr>
<td>Transport</td>
<td>-</td>
</tr>
</tbody>
</table>
Appendix 10-7. Overall confidence.

The following questions are addressed within each discipline:

- What aspects of the model (properties, specific volumes) have the highest confidence?
- What aspects have the lowest confidence?
- What are the main reasons for confidence in the model: e.g. wealth of data, consistency with other disciplines, consistency with past evolution stability over time (i.e. Few surprises as new data arrive), other..

Table 10-7. Overall confidence in the bedrock description.

<table>
<thead>
<tr>
<th>Question</th>
<th>Geology</th>
<th>Rock Mechanics and Thermal</th>
<th>Hydrogeology</th>
<th>Hydrogeochemistry</th>
<th>Transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>What aspects of the model (properties, specific volumes) have the highest confidence?</td>
<td>The geometry of site-scale structures. The large lithological units, and general trend of foliation in the well-known area of the central part of the Island.</td>
<td>Intact rock properties.</td>
<td>The effective properties, transmissivities and hydraulic conductivities respectively, of the hydrogeological zones and the sparsely fractured rock in the EPM model. Fracture sets, orientations and flow properties for fractures well above the PFL measurement threshold in the hydrogeological DFN model.</td>
<td>The general distribution of water types and gases. The range of salinity. The origin of groundwaters. The main hydrogeochemical reactions and their distribution with depth.</td>
<td>The geometry of the site-scale flow paths is well defined by the topography and the HZs. The distribution of the flow-related retention properties is well bounded by the PFL data.</td>
</tr>
<tr>
<td>What aspects have the lowest confidence?</td>
<td>The continuation of the zones outside the well-known area in the central part of the Island. The spatial distribution of small-scale features affected by different stress state Fracture properties Brittle deformation zone properties.</td>
<td>The stress state Fracture properties Brittle deformation zone properties.</td>
<td>The description of the saline water storage in matrix blocks of the EPM model. The connectivity and the description of the flow paths that are below or close to the PFL measurement.</td>
<td>The distribution of groundwater composition and long term evolution of saline groundwater at the detailed scale. The rate of hydrogeochemical reactions.</td>
<td>The heterogeneity of the transport properties in the fracture planes, where there are few data. The migration properties of the rock matrix (&quot;the immobile zones&quot;) since...</td>
</tr>
<tr>
<td>Question</td>
<td>Geology</td>
<td>Rock Mechanics and Thermal</td>
<td>Hydrogeology</td>
<td>Hydrogeochemistry</td>
<td>Transport</td>
</tr>
<tr>
<td>-------------------------------------------------------------------------</td>
<td>---------</td>
<td>---------------------------</td>
<td>--------------</td>
<td>-------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>alteration processes.</td>
<td></td>
<td></td>
<td>threshold in the hydrogeological DFN model.</td>
<td>and the accumulation of gases. The baseline hydrogeochemical conditions in HZ20A. The origin of matrix pore water and its relation to groundwaters.</td>
<td>there are few site-specific data on these. However, the importance of the fracture heterogeneity could be bounded by numerical simulations. The lack of site-specific data from Olkiluoto could be handled by using matrix data from similar sites, e.g. in Sweden and Finland.</td>
</tr>
<tr>
<td>What are the main reasons for confidence in the model e.g. wealth of data, consistency with other disciplines, consistency with past evolution stability over time (i.e. Few surprises as new data arrive), other.</td>
<td>This confidence is due to the density and number of the data used in the modelling and the understanding of the geological history.</td>
<td>This confidence is due to the large and consistent amount of data and tests now available from the ONKALO.</td>
<td>The confidence is due to the large number of fracture data for the central part of the Island and fractures above the PFL measurement limit. The EPM model is in a good agreement with the geological model. The calculated pressures in drillholes are in good agreement with observations and the calculated salinities also show a fair agreement.</td>
<td>This confidence is due to the large database and due to observations of coherent data with depth for comparable hydrogeological conditions. New data support the previous concept reported in SR2006.</td>
<td>This high level of confidence originates from the well-established geometry of the hydrogeological zones and the extensive database of PFL data that directly measures the transmissivity of the connected flow paths in the rock mass, including those outside the hydrogeological zones.</td>
</tr>
</tbody>
</table>
REFERENCES


Ekendahl, S. and Pedersen, K. 1994, Carbon transformations by attached bacterial populations in granitic ground water from deep crystalline bed-rock of the Stripa research mine. Microbiology, 140 1565-1573.

Ekendahl, S. and Pedersen, K. 1994, Carbon transformations by attached bacterial populations in granitic ground water from deep crystalline bed-rock of the Stripa research mine. Microbiology, 140 1565-1573.


Lehtonen, T. 2007. Visualization and Interpretation of the Autumn 2006 Mise-a-la-masse Survey Data at the Olkiluoto


Löfman, J. 2006. FEFTRA model development reports.


Applied Geochemistry 10, 161 - 173.


Öhberg, A. & Ahokas, H. 1991. Hydrological measurements around the VLJ repository


LIST OF REPORTS

POSIVA-REPORTS 2009

POSIVA 2009-01  Olkiluoto Site Description 2008
Posiva Oy
April 2009