R-08-84

Explorative analysis of major components and isotopes

SDM-Site Forsmark

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Preface

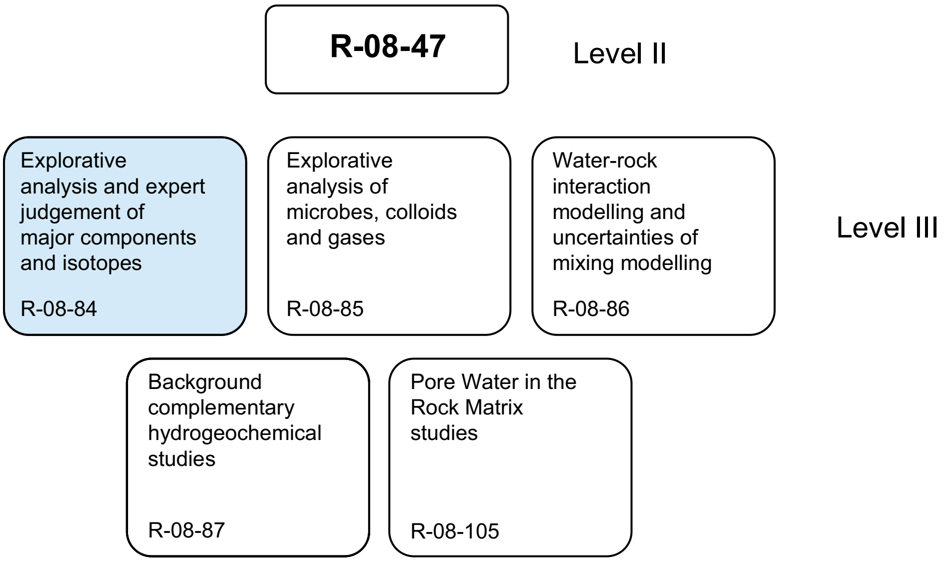
The overall objectives of the hydrogeochemical description for Forsmark are to establish a detailed understanding of the hydrogeochemical conditions at the site and to develop models that fulfil the needs identified by the safety assessment groups during the site investigation phase. Issues of concern to safety assessment are radionuclide transport and technical barrier behaviour, both of which are dependent on the chemistry of groundwater and porewater and their evolution with time.

The work has involved the development of descriptive and mathematical models for groundwaters in relation to rock domains, fracture domains and deformation zones. Past climate events are the major driving force for hydrogeochemical changes and therefore are of fundamental importance for understanding the palaeohydrogeological, palaeohydrogeochemical and present evolution of groundwater in the crystalline bedrock of the Fennoscandian Shield.

Understanding current undisturbed hydrochemical conditions at the proposed repository site is important when predicting future changes in groundwater chemistry. The causes behind copper corrosion and/or bentonite degradation are of particular interest as they may jeopardise the long-term integrity of the planned SKB repository system. Thus, the following variables are considered for the hydrogeochemical site descriptive modelling: pH, Eh, sulphur species, iron, manganese, carbonate, phosphate, nitrogen species, total dissolved solids (TDS), isotopes, colloids, fulvic and humic acids and microorganisms. In addition, dissolved gases (e.g. carbon dioxide, methane and hydrogen) are of interest because of their likely participation in microbial reactions.

In this series of reports, the final hydrogeochemical evaluation work of the site investigation at the Forsmark site, is presented. The work was conducted by SKB's hydrogeochemical project group, ChemNet, which consists of independent consultants and university researchers with expertise in geochemistry, hydrochemistry, hydrogeochemistry, microbiology, geomicrobiology and analytical chemistry etc. The resulting site descriptive model version, mainly based on 2.2 data and complementary 2.3 data, was carried out during September 2006 to December 2007. Several groups within ChemNet were involved and the evaluation was conducted independently using different approaches ranging from expert knowledge to geochemical and mathematical modelling including transport modelling. During regular ChemNet meetings the results have been presented and discussed.

The original work by the ChemNet modellers is presented in five level III reports containing complementary information for the bedrock hydrogeochemistry Forsmark Site Descriptive Model (SDM-Site Forsmark, R-08-47) level II report.



There is also an additional level III report: ‘Fracture mineralogy of the Forsmark area’ by Sandström et al. R-08-102.

Contents

1 Introduction and report structure

This level III report, ‘Explorative analysis and expert judgement of major components and isotopes’, provides some of the background material to what is extracted and presented in the level II report ‘Bedrock hydrogeochemistry Forsmark. Site descriptive modelling SDM-Site Forsmark, and the level I Chapter 9 report ’Site description of Forsmark at completion of the site investigation phase (SDM-Site Forsmark) report’.

This level III report differs from the earlier reports (version 1.2: SKB 2005) in that the hydrogeochemical evaluation is focussed on specific topics or issues of importance (more in line with version 2.1 issue report: SKB 2007) rather than a systematic evaluation of data which is largely reported in existing hydrogeochemical reports as Appendices 1 and 3.

Following this introduction (Chapter 1), the report is structured to initially provide a brief description of: a) the regional geological and hydrogeological setting of the Forsmark site, b) the location of the boreholes sampled for groundwaters, and c) the fracture mineralogy of the hydraulically active fracture(s)/fracture zone(s) sampled (Chapter 2). Chapter 3 introduces added details of the drill sites and the sampled boreholes, and outlines the different datafreeze deliveries from SKBs Sicada database. Chapter 4 addresses in detail the complexities of groundwater sampling and quality, and describes the systematic approach to categorise the groundwaters into five quality groups, i.e. Category 1–2 (good), Category 3 (intermediate), Category 4 (low) and Category 5 (very low). These subdivisions are made to facilitate the different modelling requirements of the ChemNet and HydroNet modelling groups. Chapter 5 focuses on a range of different topics/issues which require major input from all the hydrogeochemical evaluation work carried out during the past four years, for example, groundwater origin/evolution, redox conditions, residence times etc. In Chapter 6 much of the output from Chapter 5 is linked to hydrogeological and geological evidence from the Forsmark site and its surroundings to trace the history of groundwater evolution from before the last deglaciation to the present day (i.e. palaeohydrogeochemistry). Existing conceptual models have been updated and a new model constructed. Chapter 7 describes in detail the integration of all relevant hydrogeochemical results from Chapters 5 and 6 with the latest interpreted geology and hydrogeology to produce a site scale 2D conceptual visualisation of the different groundwater types that represent the Forsmark site. Two of the standard geological cross-sections (WNW-ESE and WSW-ENE) have been used for this purpose. Chapter 8 outlines the sources of uncertainty within the hydrogeochemical programme and describes how these have impacted on the programme. Finally in Chapter 9 the references are tabulated. Documentation of the groundwater categorisation procedure for both percussion and cored boreholes is appended as Appendix A and Appendix B.

Invited experts familiar with the site were invited to review and contribute to section 5.3 (A.G. MacKenzie, UK, and J. Suksi, Finland), sections 5.10 and 6.4 (H.N. Waber, Switzerland) and to provide an initial draft to section 5.4 (M. Gascoyne, Canada). In addition, several sections have benefitted from review and logistic help from the University of Zaragoza, Spain.

2 Geological and hydrogeological setting

2.1 Geological setting

The geology of the Forsmark area has been described in /Stephens et al. 2007/ and the bedrock evolution from the Palaeoproterozoic through to the Quaternary in /Söderbäck (ed) 2008/. Furthermore, the interplay between, for example, structural geological and hydrogeological features at Forsmark have been addressed in /Follin et al. 2007ab, Follin et al. 2008ab/. The summary text below is based on the data evaluation and modelling work reported in these publications.

The Forsmark site is located north-east of Forsmark village along the Baltic Sea coast in an area that contains three regionally significant deformation zones (Singö, Eckarfjärden and Forsmark). These zones dip steeply and strike WNW-ENE and NW-SE (Figure 2-1). In several parts of the area, outcrops are limited, especially away from the coast. The bedrock is dominated by different types of metamorphosed granitoid with subordinate felsic to intermediate metavolcanic rocks, metamorphosed diorite or gabbro, pegmatite or pegmatitic granite and amphibolite (Figure 2-1). These rocks formed between 1.89 and 1.85 thousand million years ago (1.89–1.85 Ga).

A penetrative, ductile tectonic fabric developed between 1.87 and 1.85 Ga during the Svecokarelian orogeny, when temperatures exceeded 600°C and the rocks were situated at mid-crustal depths. After 1.85 Ga, the rocks started to cool below 500°C. Areas where the bedrock is banded and/or affected by a strong, ductile tectonic foliation (dotted raster in Figure 2-1) can be separated from areas where the bedrock is folded and more lineated in character (dotted raster absent in Figure 2-1). The former are inferred to have been affected by higher ductile strain. They anastomose around the more folded and lineated bedrock with lower ductile strain that are restricted to several tectonic lenses. The candidate area is situated in the north-western part of one of these tectonic lenses and includes the target area in its north-westernmost part, between Bolundsfjärden and the nuclear power plant. The bedrock inside this tectonic lens is relatively homogeneous and is dominated by medium-grained metagranite with subordinate pegmatite or pegmatitic granite, amphibolite and finer grained metagranitoid. The lithology and deformational characteristics are more complex outside the lens. The rocks in these marginal domains dip steeply towards the south-west.

Following these early developments, ductile-brittle and brittle deformation occurred several times during the Proterozoic, related to major tectonic activity probably during the later part of the Svecokarelian (1.80–1.70 Ga), Gothian (1.70–1.60 Ga) and Sveconorwegian (1.1–0.9 Ga) orogenies. This has resulted in the activation and subsequent reactivation of the different fracture systems. A second geological process has also affected the bedrock at several times during the Proterozoic and Phanerozoic. This process involved loading by sedimentary rocks or by ice during cold, glacial periods and, subsequently, unloading related to denudation of this younger material. This process has occurred at several times during the long geological history of the bedrock and each unloading phase resulted in exhumation of the Proterozoic crystalline bedrock.

The geological modelling work at Forsmark /Stephens et al. 2007/ has addressed rock domains, deformation zones and fracture domains in the bedrock. These three entitites are summarised below. Rock domains occupy the whole rock volume and each rock domain consists of two components; the bedrock along deformation zones and the bedrock between deformation zones which comprises one or more fracture domains.

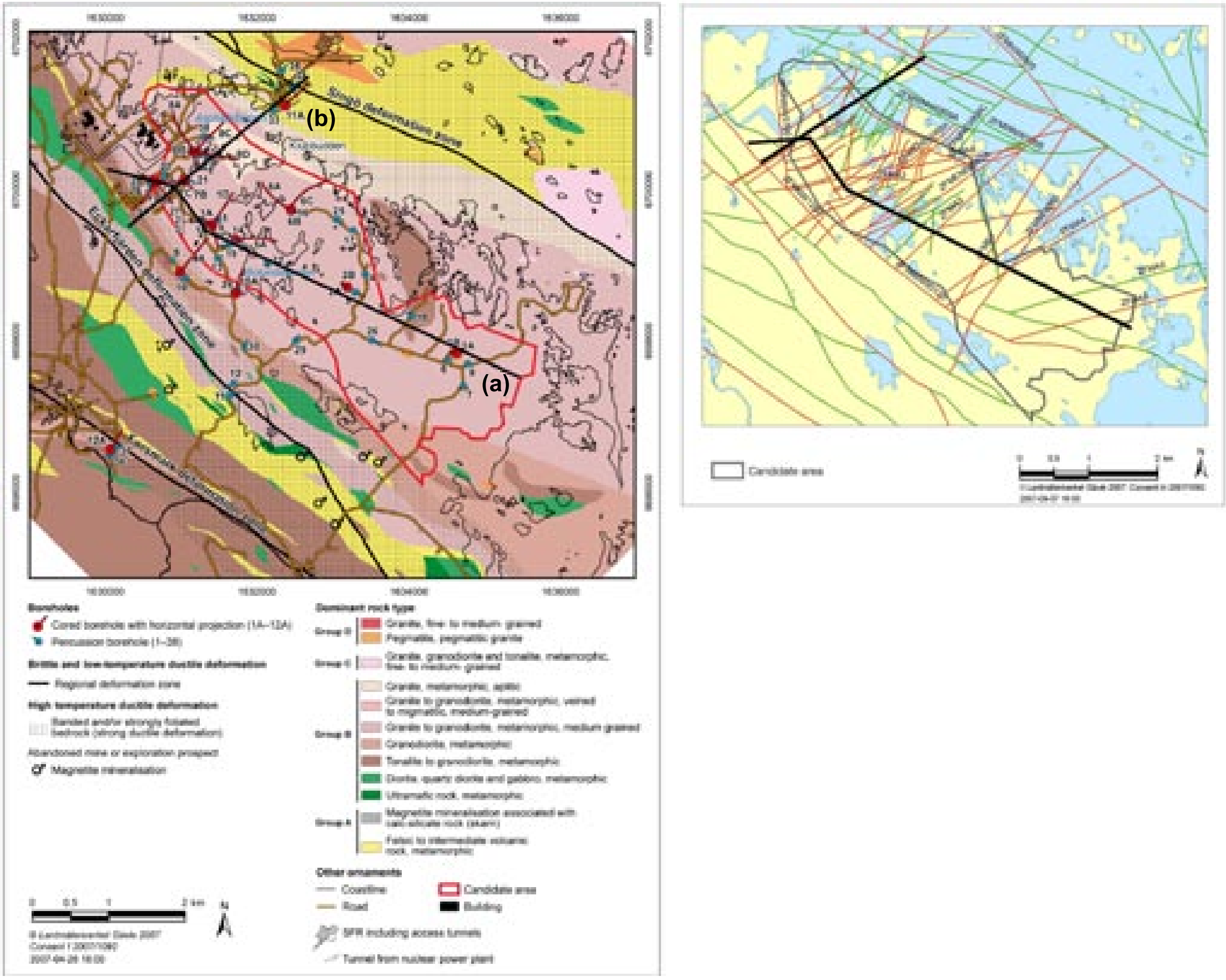


Figure 2-1. Cored and percussion borehole locations in relation to the bedrock geology of the Forsmark area. The approximate positions of the WNW-ESE (a) and WSW-ENE (b) cross-sections described in Chapter 7 are indicated /Stephens et al. 2007/.

2.1.1 Rock domains

Rock domains refer to rock volumes where the bedrock shows similar composition, grain size, degree of bedrock homogeneity, and degree and style of ductile deformation. Rock domains RFM029 and RFM045 (Figure 2-2) comprise the target volume and are of most significance in the context of the site description and modelling work. Rock domain RFM029 dominates the central part of the target volume and is volumetrically the most significant domain from a repository construction viewpoint; the subordinate rock domain RFM045 occurs in the northern part of the target volume (Figure 2-2). The bedrock in these domains predominantly consists of medium-grained metagranite with, in order of decreasing importance, subordinate pegmatite or pegmatitic granite, amphibolite and fine- to medium-grained metagranitoid. The rocks are affected by regional amphibolite-facies metamorphism and, in rock domain RFM045, by the high-temperature alteration referred to as albitisation.

Rock domains RFM029 and RFM045 are situated in the core of a major synform that plunges 55–60° to the SE (Figure 2-2). Folding of the ductile tectonic foliation inside these two domains and the development of a linear ductile fabric is a characteristic structural feature.

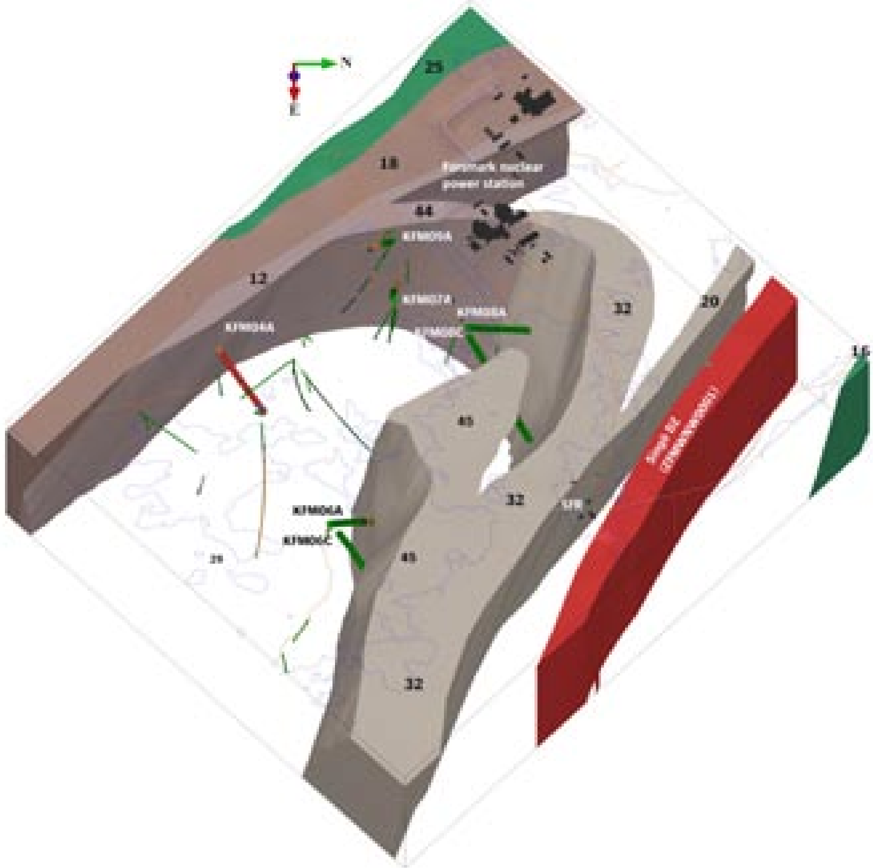


Figure 2-2. *Three dimensional model of the moderately- to steeply-plunging synform structure which characterises the target volume. The model is viewed to the west from approximately the position of SFR. The regionally significant Singö deformation zone is shown in the foreground. The rock domains inside the target volume are numbered; several domains, including RFM029, are unshaded in order to display the structural style at the Forsmark site. Note especially the moderately- to steeply-plunging synform that is defined by the boundary between domain RFM029 and domains RFM032 and RFM044. The dominant rock type in each domain is depicted by different colours (see Figure 2-1). Boreholes marked with the help of larger cylinders (KFM04A, KFM06A, KFM06C, KFM07A, KFM08A, KFM08C and KFM09A) constrain the boundaries between different domains /Stephens et al. 2007, Figure 4-5/.*

Virtually all the other rock domains occur along the limbs of the major fold structure, both to the north-east and to the south-west (Figure 2-2). The marginal rock domains outside the target volume share the property that they are affected by intense ductile strain with strongly foliated and lineated rocks, and locally an intense tectonic banding.

2.1.2 Deformation zones

Deformation zones refer to parts of the bedrock along which there is a concentration of strain. Most deformation zones at Forsmark are brittle structures, i.e. they are fracture zones. Three important sets of deformation zones have been recognised (Figures 2-3 and 2-4):

- Vertical and steeply dipping (to the south-west) deformation zones that strike WNW-ENE or NW-SE and are prominent outside the target volume. These zones generally show complex, ductile and brittle deformation and are represented by the Singö, Eckarfjärden and Forsmark zones. These three zones show a trace length at the ground surface which is longer than 10 km, i.e. they are regionally significant zones.
- Vertical and steeply dipping fracture zones that strike ENE-WSW to NNE-SSW and are prominent inside the target volume. The zones that belong to this set inside the target volume show a trace length at the ground surface which is about 3,000 m or less.

- Gently dipping fracture zones that dip to the SE and are conspicuous outside the target volume in the south-eastern part of the candidate volume. This set includes the gently dipping fracture zone ZFMA2 which effectively forms the southern boundary to the target volume. Relative to the other two sets of deformation zones, the gently dipping zones contain a higher frequency of open fractures and crush rock. Many of these zones extend to at least 1,000 m depth, and they play an important role both hydrogeologically and hydrogeochemically.

Extracts of the 3D deterministic models for deformation zones (stage 2.2; see /Stephens et al. 2007/), both on a regional and on a local scale, are shown in Figures 2-4 and 2-5, respectively. The regional model (Figure 2-4) includes all the vertical and steeply dipping zones that are longer than 3,000 m at the ground surface and all the gently dipping zones inside this model volume. By contrast, the local model includes all the vertical and steeply dipping zones longer than 1,000 m and all gently dipping zones that are present inside this more restricted model volume. An extract of the local model, which only includes the dominant vertical and steeply dipping zones, is shown in Figure 2-5. The target volume is situated in the central part of the local model volume.

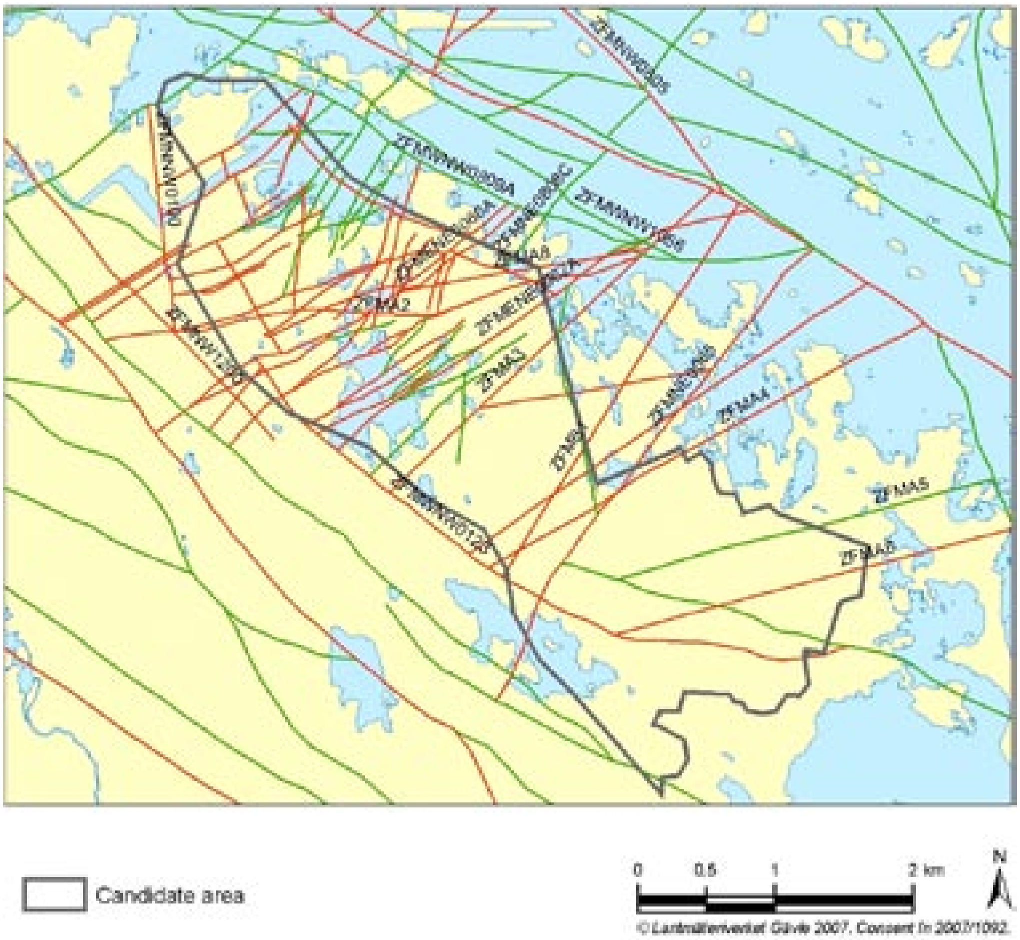


Figure 2-3. Major deformation zones in the Forsmark area. Only the most relevant zones are labelled to correspond to the cross-sections later used to conceptualise and visualise the hydrogeochemical data (Chapter 7).

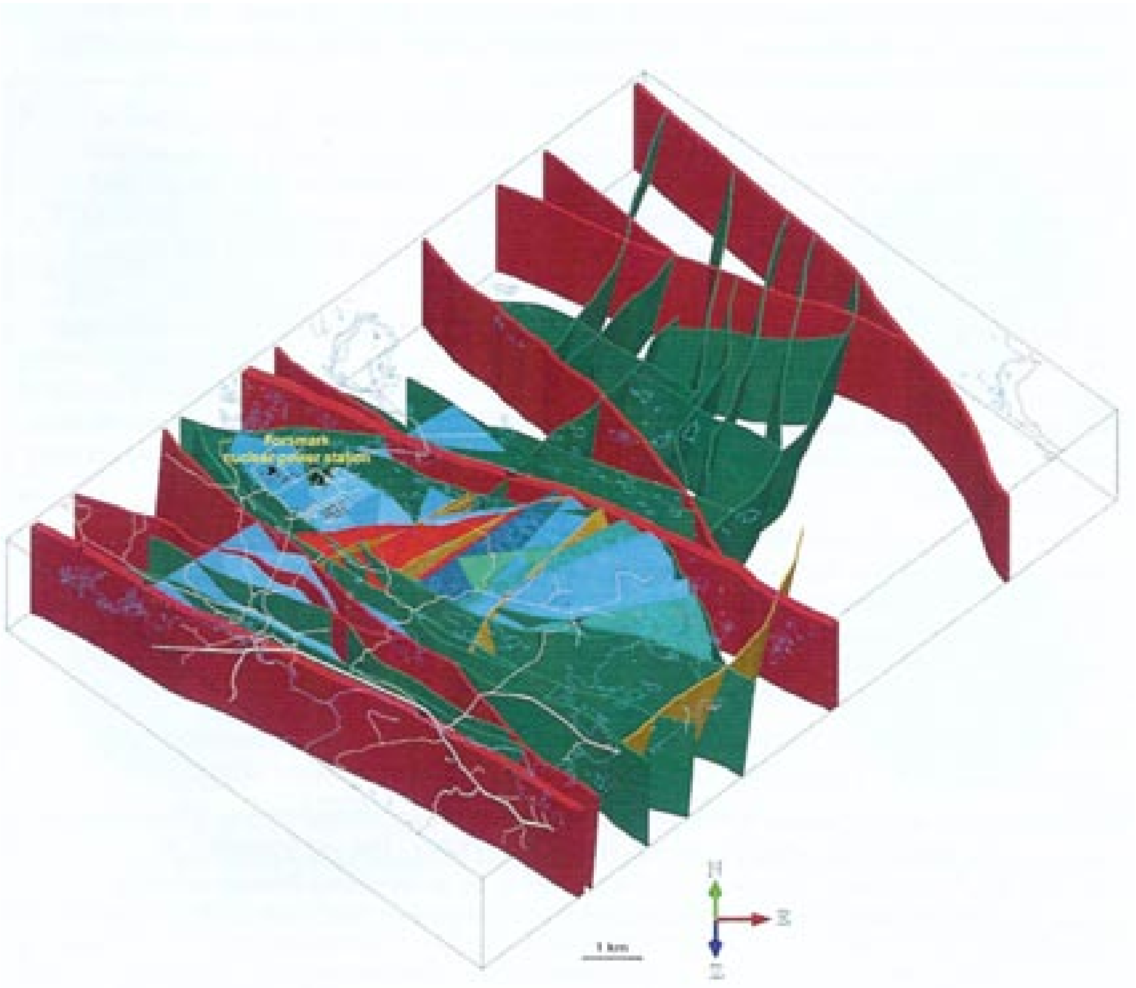


__Figure 2-4.__ Three dimensional model of all deformation zones at the regional scale (compare with Figure 2-3). Zones marked in red have a trace length at the surface longer than 10,000 m (regional deformation zones). Zones marked in green and beige are steeply dipping zones between 3,000 and 10,000 m in length. The beige colour indicates the few zones of this size that transect the tectonic lens. The zones marked in blue and red are gently dipping; the sharp red colour marks the major gently dipping deformation zone ZFMA2. The model is viewed to the north /Stephens et al. 2007, Figure 5-20/.

Connected, open fractures have been modelled in 3D with a stochastic representation of the individual fractures using the discrete fracture network (DFN) concept /Follin et al. 2008a/. Figure 2-7 shows a NW-SE cross-section of a stochastic simulation of such features in fracture domains FFM01, FFM02 and FFM03 along the candidate volume (compare with Figure 2-6). The orientation of this cross-section is similar to that shown below in Figure 2-8. The simulation indicates that these three fracture domains have significantly different intensities of connected open fractures. The intensity of such fractures is important when interpreting and discussing groundwater flow and the advective transport of different groundwater types (solutes) (cf. section 2-3 below). In particular, below –400 m elevation in fracture domain FFM01, the connected open fractures are compartmentalised and the intensity of these fractures is close to the percolation threshold. As a result of the high horizontal stresses and the structural anisotropy in the bedrock, the connected open fractures in the bedrock segment structurally beneath the gently dipping zones ZFMA2 and ZFMF1, i.e. inside the target volume, are predominantly subhorizontal or gently dipping, with second order steeply dipping sets around NE and NS. Moreover, the majority of the flowing fractures observed in the cored boreholes are subhorizontal or dip gently (up to 80%).

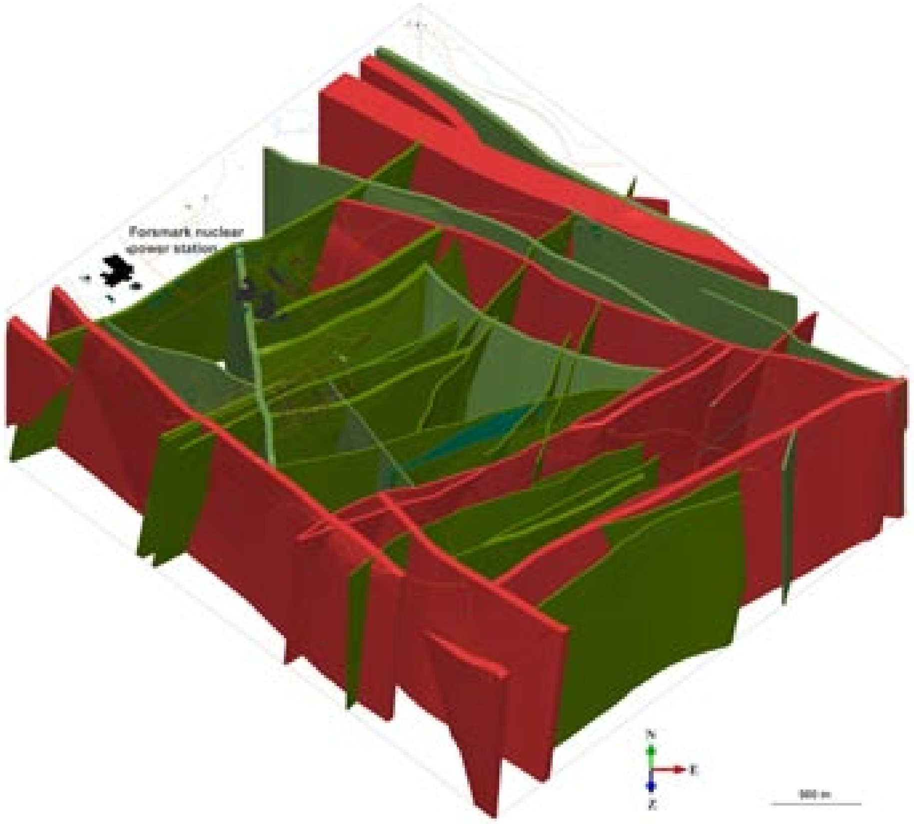


Figure 2-5. *Three dimensional model of the vertical- to steeply dipping deformation zones at the local scale. Note the concentration of vertical and steeply dipping deformation zones that trend ENE and NNE in the central part, i.e. the target volume. The model is viewed to the north. Zones marked in red have a trace length at the surface longer than 3,000 m; zones marked in green are less than 3,000 m in length /Stephens et al. 2007, Figure 5-12/.*

2.1.3 Two-dimensional cross-sections

The major geological features of the candidate volume are further detailed in two strategically selected cross-sections that integrate rock domains and deformation zones. These sections have been extracted from the regional geological models (stage 2.2) for the site /Stephens et al. 2007/. The location of the profile lines are shown in Figure 2-1:

- A WNW-ESE section (Figure 2-8) connecting boreholes KFM09A and B, KFM07A, B and C, KFM01A, B, C and D, KFM05A, KFM02A and B, KFM03A and B as well as the associated percussion boreholes.
- A WSW-ENE section (Figure 2-9) connecting boreholes KFM09A and B, KFM07A, B and C, KFM08A, B, C and D and KFM11A, as well as the associated percussion boreholes.

The geology of the WNW-ESE section through the central part of the candidate volume is dominated by medium-grained metagranite (rock domain RFM029) with minor metatonalite (rock domain RFM017). The bedrock in rock domain RFM044 consists of the same granitic rocks as in RFM029 but is affected by stronger ductile deformation, while the bedrock in rock domain RFM034 resembles that in RFM029.

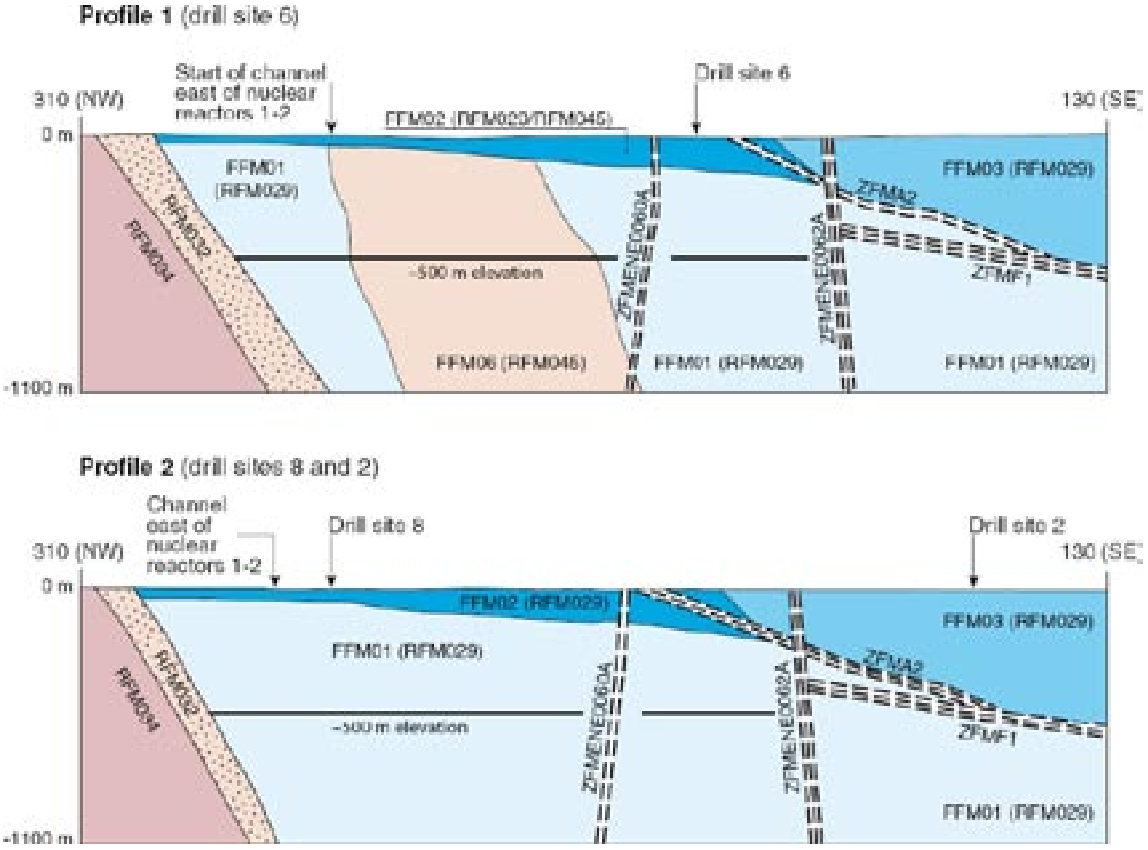


Figure 2-6. *Simplified NW-SE profiles across the target volume that intersect drill sites 2 and 8 (Profile 1) and drill site 6 (Profile 2) (cf. Figure 2-1 for location). The labelled fracture domains (FFM01, FFM02, FFM03 and FFM06) occur inside rock domains RFM029 and RFM045. Note the major gently dipping deformation zones ZFMA2 and ZFMF, which essentially divide the candidate area into FFM03 (hanging wall) and fracture domains FFM01, 02 and 06 (footwall). The target volume is situated inside the footwall bedrock segment. Reference to average repository depth is shown by the black line at –500 m elevation and 'channel' refers to an excavated link between the Baltic Sea and the nuclear power plant (not shown) /Olofsson et al. 2007, Figure 5-1/.*

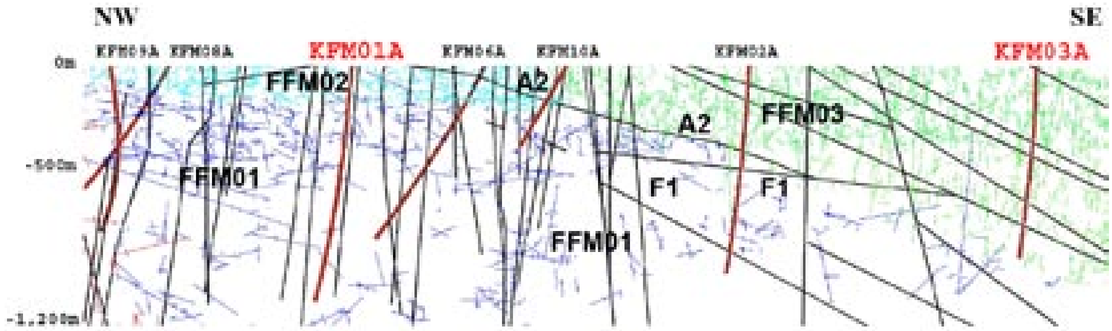


Figure 2-7. *WNW-ESE cross-section through the central part of the candidate area showing an example of the DFN model realisation with connected open fractures in fracture domain FFM01 (dark blue), FFM02 (turquoise) and FFM03 (green). Note the absence of connected open fractures in KFM01A below an elevation of approximately –300 m /Follin et al. 2008ab/.*

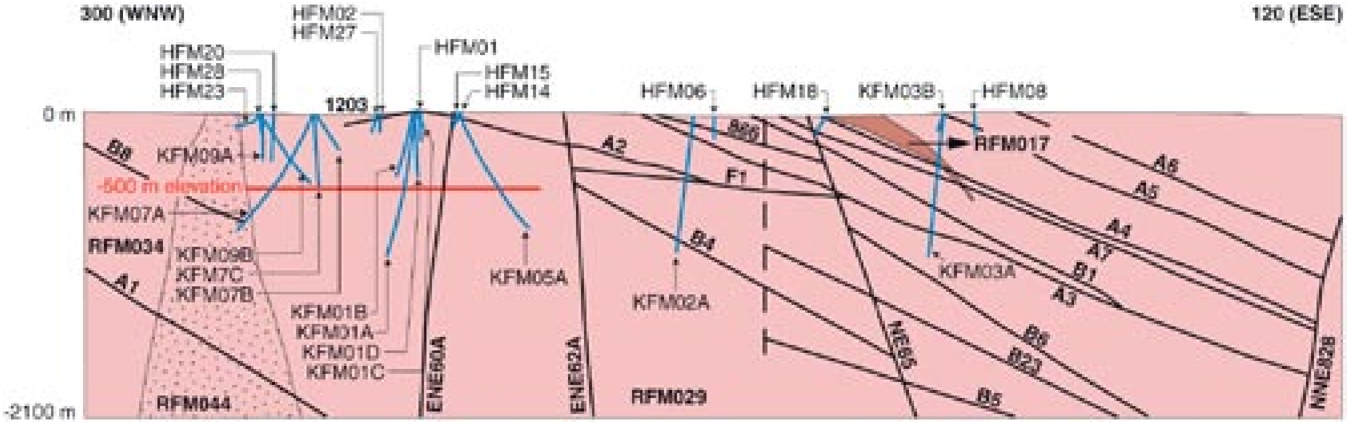


Figure 2-8. WNW-ESE 2D cross-section through the central part of the candidate area /Stephens et al. 2007, Figure 5-21a/. The important gently dipping deformation zones identified with reflection seismic data are highlighted, in particular ZFMA2 and ZFMF1. Together with the steeply dipping zone ZFMNE0065, these zones essentially divide the candidate volume into hanging wall (to the SE) and footwall (to the NW) bedrock segments. Since this cross-section has been extracted from the regional model, rock domain 29 is referred to as RFM029R. The potential repository inside the target volume is located inside rock domain 29 in the footwall bedrock segment. See text for further description.

There is a significant structural difference in the deformation zone pattern on both sides of the gently dipping deformation zones ZFMA2 and ZFMF1. These zones essentially divide the candidate volume into a hanging wall bedrock segment to the south-east and a footwall bedrock segment to the north-west (see also Figure 2-6). The hanging wall bedrock contains an increased number of gently dipping fracture zones, many of which extend down to at least 1,000 m depth (Figure 2-8). By contrast, there are very few gently dipping zones in the footwall bedrock (Figure 2-8). This difference is also steered by the older anisotropy at the site, with gently dipping ductile structures and rock contacts in the south-eastern part of the candidate volume and more steeply dipping structures and contacts in the north-western part, in different parts of the major fold structure shown in Figures 2-2 and 2-9 /Stephens et al. 2007/. In addition, it needs to be kept in mind that the bedrock in the north-western part of the candidate volume, on both sides of zones ZFMA2 and ZFMF1, is intersected by a number of steeply dipping fracture zones, which strike ENE-WSW to NNE-SSW (see Figure 2-3).

The WSW-ENE 2D cross-section (Figures 2-1 and 2-9) has largely been described above in the context of Figure 2-2. The cross-section represents a slice through the major SE-plunging synform. It shows how rock domain RFM029 forms the core of the major synform inside the tectonic lens and how other rock domains are situated along the limbs of this major structure. The potential repository inside the target volume is located inside rock domain 29 in the core of the synform.

2.1.4 Concluding remarks

Most of the hydrogeochemical data evaluated originate from deformation zones and only a limited amount of data come from the bedrock in the contiguous fracture domains. Moreover, some of the data in the fracture domains may have been influenced, to varying extent, by groundwater from nearby deformation zones, since sampling is possible only in fractures with groundwater flow. Such fractures need to be both transmissive and connected to these deformation zones. Examples include the deepest groundwaters sampled from borehole KFM03A and some upper and intermediate groundwaters from borehole KFM01D. Furthermore, there is a spatial homogeneity in the fracture groundwater and matrix porewater chemistry which begins to become evident throughout the Forsmark candidate volume beneath around 600–700 m depth. As a consequence of these considerations, it has generally proven difficult to relate the hydrogeochemical data to the fracture domain concept. The only clear distinction is the hydrochemical difference between fracture domain FFM02 and the underlying FFM01 in the footwall bedrock segment.

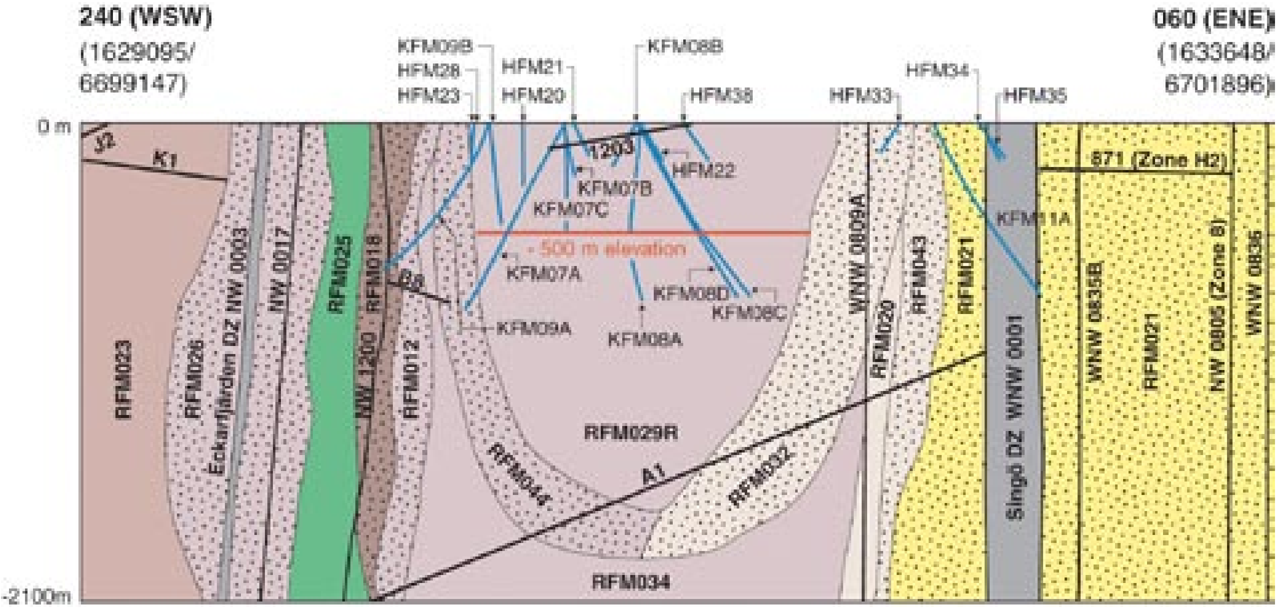


Figure 2-9. *The WSW-ENE 2D cross-section showing the main deformation zones, the borehole positions (marked in blue; some extrapolated), and the main rock domains constituting the tectonic lens and its surroundings. The estimated repository depth at 500 m is marked in red. Note that boreholes KFM08A/B/C, KFM07A/B/C and KFM09B are located within the tectonic lens, and that KFM09A, and the lower part of KFM7A and KFM11A, penetrate the periphery of the lens towards the Eckarfjärden DZ and Singö DZ respectively. Since this cross-section has been extracted from the regional model, rock domain 29 is referred to as RFM029R /Stephens et al. 2007/.*

It is the hydrogeology of the water-conducting fractures within the fracture domains and the deformation zones embedded in the fracture domains that are of key importance to hydrogeochemistry. Together with the hydrogeochemistry, these water-conducting structures, in turn, will influence the distribution of the porewater chemistry in the rock matrix. Bearing in mind the considerations above, it has proven more useful to address the hydrogeochemical data in relation to their spatial location with respect to the footwall and hanging wall bedrock segments as discussed above. The key features of the structural-mechanical properties of importance for the hydrogeochemical and hydrogeological modelling at Forsmark are as follows /Stephens et al. 2007, Follin et al. 2008a/:

- A pronounced bedrock anisotropy, established at an early stage in the geological history in the ductile regime, steered the overall occurrence and character of younger brittle structures at the site.
- The major gently dipping deformation zones ZFMA2 and ZFMF1 divide the candidate area bedrock into a footwall bedrock segment (i.e. target volume to the north-west) and a hanging wall bedrock segment to the south-east.
- The footwall bedrock is inferred to have higher rock stresses than the hanging wall bedrock and is primarily composed of fracture domain FFM01. Fracture domain FFM02 is situated closer to the surface, predominantly in the footwall bedrock, and contains a conspicuously higher frequency of open fractures relative to that observed in fracture domain FFM01. Release of stress along subhorizontal and gently dipping fractures characterise this domain. The fractures consist of both reactivated older fractures and newly formed sheet joints.
- The hanging wall bedrock is intersected by several gently dipping deformation zones, many of which extend to at least 1,000 m depth, or more. It is primarily composed of a single fracture domain, FFM03.

- The intensities of connected open fractures are significantly different for these three fracture domains. For instance, below –400 m in the footwall bedrock (i.e. fracture domain FFM01), the connected network of open fractures is considerably compartmentalised and close to the percolation threshold, which implies a restricted groundwater circulation at repository depth. The observed open fractures are predominantly subhorizontal or gently dipping.

2.2 Fracture filling studies

Detailed investigations of the fracture mineralogy and altered wall rock have been carried out as part of the Forsmark site characterisation programme. /Sandström et al. 2008/ summarises and evaluates the data obtained during the detailed fracture mineralogical studies, and also includes information derived from the extensive core mapping that has been carried out within the programme. The report includes descriptions of the identified fracture minerals, their chemical composition and petrogeneses, and the sequence of fracture mineralisations in the area. Special focus has been put on the chemical and stable isotopic composition of calcite to obtain palaeo-hydrogeological information. Chemical analyses of bulk fracture filling material have been used to identify possible sinks for certain elements and also to identify minor mineral phases which can be overlooked by X-ray diffraction (XRD).

2.2.1 General characteristics

The relative abundance of the different fracture minerals have been evaluated based on core mapping (Boremap) data combined with supporting analyses to identify minerals difficult to determine macroscopically. The most common fracture minerals are chlorite/corrensite and calcite. Other minerals frequently found are laumontite, quartz, adularia, albite, prehnite, epidote, haematite and pyrite. Minerals found as minor occurrences include asphaltite, analcime and goethite.

Clay minerals have been identified using XRD analyses and the most common varieties are corrensite > illite > mixed layer clays > smectite > kaolinite, vermiculite and other swelling clays. No other carbonates than calcite have been identified and the only sulphate mineral identified is barite which occurs in very small amounts (e.g. inclusions in galena); gypsum has not been identified in any of the fractures studies. Pyrite makes up more than 99% of the identified sulphides, together with small amounts of galena, chalcopyrite and sphalerite.

Potential differences in fracture mineralogy between the different fracture domains have been studied and it can be concluded that:

- With the exception of asphaltite and goethite, which almost exclusively are found in open fractures within fracture domain FFM02 (and probably in the upper part of FFM03), the same fracture mineralogy is found in fracture domains FFM01, FFM02, FFM03 and FFM06, although the proportion of the different minerals may vary.
- Clay minerals (Figure 2-10) also occur most abundantly in open fractures in FFM02 but are found in all other fracture domains within the target volume as well.
- Other minerals (e.g. chlorite) show little or no variation with depth. Clay minerals (Figure 2-10) are found more abundantly in fractures in the upper part of the bedrock but are also found at greater depths. The calcite ± quartz ± pyrite assemblage (i.e. generation 3; see below) is most common in the upper 350 m of the bedrock, but in the near-surface environment there is no evidence that calcite and pyrite have decreased in frequency. The presence of goethite in hydraulically conductive zones, however, suggests an input of oxidising water associated mainly with subhorizontal zones during some occasions in the past.

The dominating fracture assemblages in the hydraulically conductive fractures are chlorite + calcite ± others and calcite ± quartz ± pyrite (i.e. typical assemblage of the Palaeozoic Generation 3 fractures).

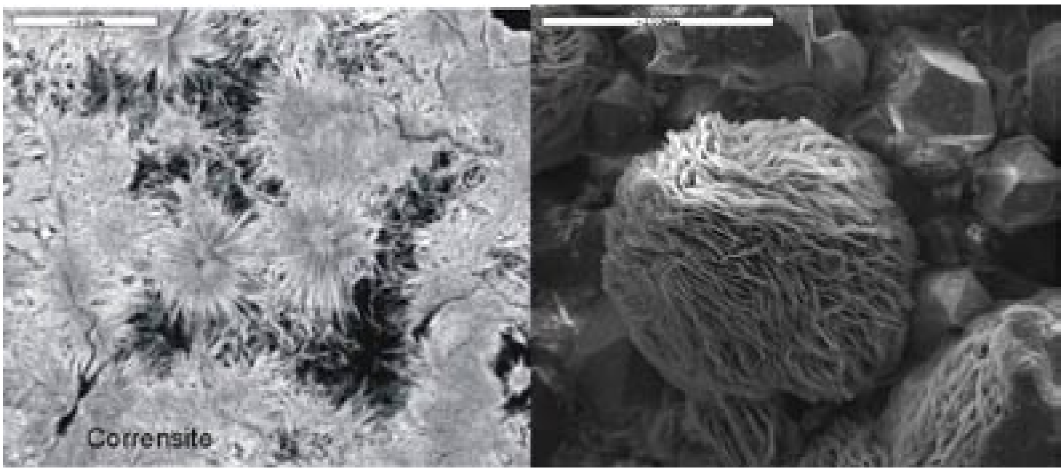


Figure 2-10. Backscattered electron images of corrensite. The left image is from a thin section from KFM05A 428.00–428.13 m, scale bar is 50 µm. The right image is from KFM05A 938.00–938.18 m, scale bar is 200 µm.

2.2.2 Sequence of fracture mineralisation events

Four different generations of fracture mineralisation have been distinguished with high confidence /Sandström et al. 2006b, Sandström et al. 2008/.

Generation 1 (Pre-Sveconorwegian)

Generation 1 is dominated by epidote, quartz and Fe-rich chlorite and brittle-ductile cataclasites sealed with these minerals at temperatures >200°C. Generation 1 minerals are commonly found in subhorizontal to gently dipping fractures or in steep fractures trending WNW-ESE to NW-SE. These minerals precipitated between 1.8 and 1.1 Ga ago.

Generation 2 (Sveconorwegian)

Generation 2 consists of a sequence of fracture minerals precipitated during hydrothermal conditions (around 150–280°C). ^{40}Ar/^{39}Ar ages indicate that the minerals precipitated (or the isotope system was reset due to hydrothermal circulation) between 1.1 and 1.0 Ga ago, corresponding to an early phase of the Sveconorwegian orogeny in western Scandinavia. Both reactivation and formation of new fractures and breccias is indicated during this period. The dominating minerals are adularia, albite, prehnite, laumontite, calcite, chlorite and sub-microscopic grains of haematite. Generation 2 minerals are preferably found in steep, ENE-WSW to NNE-SSW and NNW-SSE fractures.

Generation 3 (Palaeozoic)

Generation 3 consists of minerals precipitated under low temperature conditions during the Palaeozoic. The most abundant are calcite, quartz, pyrite, corrensite and asphaltite. The formation fluid was influenced by organic material which may have originated in a sedimentary cover rich in organics. The formation temperature was around 60–100°C although higher temperatures (160–190°C) may have been reached locally in the fracture system. Both reactivation of older fractures filled with generation 1 and 2 minerals and formation of new fractures are associated with precipiation of generation 3 minerals. The minerals are commonly found in both the steep fracture sets and in subhorizontal to gently dipping fractures.

Generation 4 (Late Palaeozoic-Present)

Generation 4 is dominated by chlorite/clay minerals and thin precipitates of late calcite mostly associated with the hydraulically conductive fractures and deformation zones. Precipitation of these minerals has most likely occurred over a long period of time (since the Late Palaeozoic?) and during different events. Most generation 4 minerals occur in subhorizontal to gently dipping fractures but have also been identified in steep WNW-ESE, NW-SE, NNW-SSE, NNE-SSW and ENE-WSW trending fractures. It is inferred that the hydraulically conductive zones are very old structures (i.e. Proterozoic to Palaeozoic). However, some of the near-surface, subhorizontal to gently dipping fractures may be relatively young (i.e. Palaeozoic to the present) Fractures without any visible minerals (mapped as 'no mineral' during the drill core mapping) are also interpreted to belong to generation 4, although their abundance and origin need to be addressed separately in a special study.

2.2.3 Wall rock alteration

The character and properties of altered (i.e. red stained) rock that occurs adjacent to fractures with generation 1 and 2 minerals (Figure 2-11) are related to changes in mineralogy, geochemistry, porosity and redox capacity when compared to the fresh rock /Sandström and Tullborg 2006, Sandström et al. 2008/.

The major mineralogical changes in the altered rock are an almost complete saussuritisation of plagioclase, chloritisation of biotite and to some extent haematisation of magnetite. The plagioclase of oligoclase composition has been replaced by a mineral assemblage consisting of albite, adularia, sericite, epidote, haematite and calcite. The red staining of the rock is due to disseminated sub-microscopic haematite grains within and along the grain boundaries of the saussuritised plagioclase.

This hydrothermal staining normally extends a few centimetres perpendicularly out from the fractures into the wall rock, although more extensive zones do exist, often associated with penetrative networks of thin fractures. However, because the alteration (especially the chloritisation) extends farther into the rock than the staining suggests, the amount of altered rock mapped as 'oxidised' should be seen as a minimum value of the alteration.

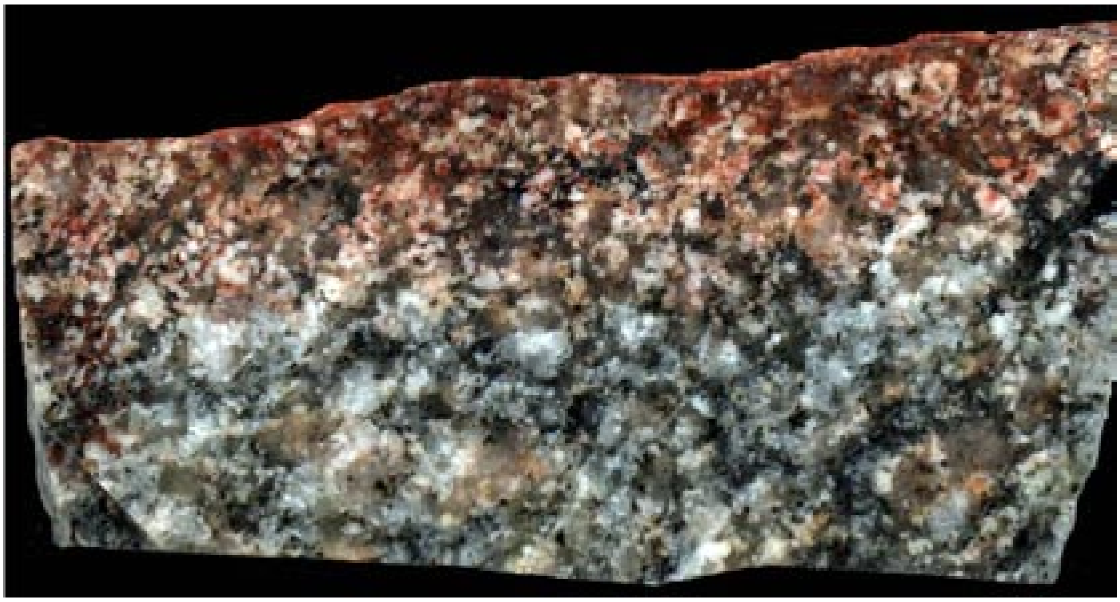


Figure 2-11. *Red stained hydrothermally altered rock adjacent to a laumontite sealed fracture. The red staining can be seen to gradually disappear about 1.5 cm out from the fracture. Sample KFM09A 145.84 m. The base of the picture is approximately 4.5 cm.*

The changes in geochemical composition between fresh and altered rock are relatively small. The major changes include an increase in Na and LOI (Loss On Ignition), whereas Ca, Si and Fe^{2+} decrease in the altered rock. Most trace elements have been immobile on the rock scale with a small decrease in Sr in the altered rock as the most evident change. On the microscale (between and within mineral grains) the mobility of both major and trace elements have been more extensive /Sandström et al. 2008/.

An increase in the connected porosity in the altered rock can be seen, most likely due to the chloritisation of biotite and an increase in the number of micro-fractures.

A small increase in the degree of oxidation can be seen in the altered rock but this change is not as evident as may be suggested by the red staining. The measured mean total oxidation factor (Fe^{3+}/Fe_{total}) increases from 0.20 in fresh rock to 0.28 in altered rock, indicating that most Fe still is in the Fe^{2+} oxidation state even in the altered rock.

2.3 Hydrogeological setting

2.3.1 Surface to near-surface features

The Forsmark candidate area is characterised by low relief with small-scale topography and is almost entirely located below 20 m.a.s.l. /e.g. Bosson et al. 2008/. The Quaternary till deposits that characterise the surface are less than 20 m thick and cover around 90% of the ground surface; rock outcrops are common. All known regolith in the Forsmark area, as generally in northeastern Uppland, has been deposited during, or after the Weichselian glaciation (i.e. during the last 115,000 years; /Söderbäck (ed) 2008/). The oldest deposits are of glacial origin and are deposited directly from the Weichselian ice sheet or by water from the melting ice. The deposits typically are poorly developed comprising young and unweathered soils with a high content of calcium carbonate in the gravel and fine fractions, and the occurrence of till with a high clay content. Hydraulic conductivities vary within these deposits with the upper soil profile (approximately 0.6 m) characterised by high values ($1.5 \cdot 10^{-5}$ ms^{-1}), the deeper coarse tills at lower values ($1.5 \cdot 10^{-6}$ ms^{-1}), and the underlying fine-grained till at even lower values ($1.5 \cdot 10^{-7}$ ms^{-1}).

The annual precipitation and runoff are 560 and 150 mm, respectively. Groundwater levels in these Quaternary deposits are very shallow and, on average, less than 0.7 m below ground during 50% of the year. With abundant recharge the groundwater levels quickly rise resulting in lateral flow and surface water discharge. The region consists of small catchment areas characterised by localised shallow groundwater flow systems. Wetlands are frequent and cover between 25 and 35% of the surface in some of the delineated sub-catchments. The main lakes, Fiskarfjärden, Bolundsfjärden, Eckarfjärden and Gällsboträsket, are shallow with mean and maximum depths ranging from approximately 0.1 to 1 m and 0.4 to 2 m, respectively. Sea water flows into the most low-lying lakes during events of very high sea water levels.

2.3.2 Near-surface to bedrock interface

From a hydrochemical viewpoint the recharging waters entering the bedrock from the Quaternary deposits defines the important (altered) meteoric end member for the bedrock groundwater evaluation. For most of the target area there is a close correlation between the topography and the groundwater levels in the Quaternary deposits, which is not the case for the upper bedrock environment. For example, high transmissivity is indicated in the upper bedrock by low groundwater level gradients which contrast with groundwater levels in the till which are in general considerably higher than in the bedrock. Hence, local, small-scale recharge (downward flow) and discharge (upward flow) areas, involving groundwater flow systems restricted to the Quaternary deposits, will overlie the more large-scale flow systems associated with groundwater flow in the bedrock. Also, in the middle of Lake Bolundsfjärden, located in the central part of the candidate area, the lake level and the groundwater level in the till are considerably higher than the groundwater levels in bedrock down to 200 m depth, indicating a downward flow gradient from the lake and Quaternary deposits to the bedrock /Follin et al. 2007a, Söderbäck (ed) 2008/.

The flow systems around and below the lakes are quite complex. The lake water/groundwater level relationship, under natural as well as disturbed conditions, indicates that the lake sediments and the underlying till have low vertical hydraulic conductivities. This means that groundwaters below the lakes have relict marine chemical signatures, whereas groundwaters in the surface riparian zones are fresh.

The transition from near-surface to upper bedrock is illustrated by /Follin et al. 2007ab/ when introducing the concept of the shallow bedrock aquifer (Figure 2-12).

The shallow bedrock aquifer concept centres on the horizontal/subhorizontal sheet joints shown in the figure. This part of the upper bedrock (0–150 m) is considered to be hydraulically anisotropic due to a lattice of intersecting near-surface joints and gently dipping single fractures /Follin et al. 2007ab/. The groundwater flow field is considered horizontally anisotropic and flow rates are high. When the meteoric recharge waters enter the shallow bedrock aquifer they mix with existing groundwaters in the fractures and are rapidly transported to be discharged towards the Baltic Sea to the NE of the candidate site. Figure 2-13 shows the aerial extent of the shallow bedrock aquifer which underlines its importance to the target volume.

This structural lattice therefore forms the shallow bedrock aquifer, effectively limiting direct meteoric recharge to deeper bedrock levels. Some deeper recharge of meteoric water is likely to occur where outcropping, steeply dipping deformation zones coincide with higher surface elevations south-west of the candidate area /Follin et al. 2008ab/.

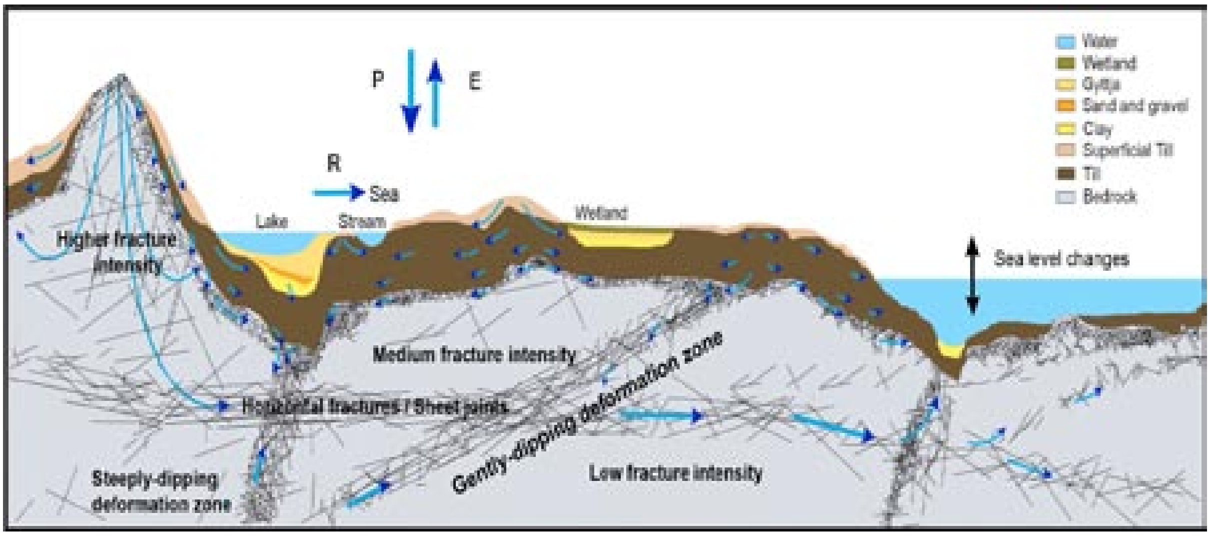


Figure 2-12. *East to west cross-section of the Forsmark target area illustrating the sequence and groundwater flow properties from surface Quaternary regolith sediments to the approximately upper 150 m of the bedrock which represents the shallow bedrock aquifer. P=precipitation, E=evapotranspiration, R=runoff. The lattice of horizontal fractures/sheet joints, outcropping deformation zones and single fractures in between the deformation zones is probably heterogeneous but in many places it is highly transmissive. The lattice is found to short circuit the recharge from above as well as the discharge from below. That is, the groundwater levels in the Quaternary deposits and at depth are both higher than in the near-surface bedrock /Follin et al. 2007ab/.*

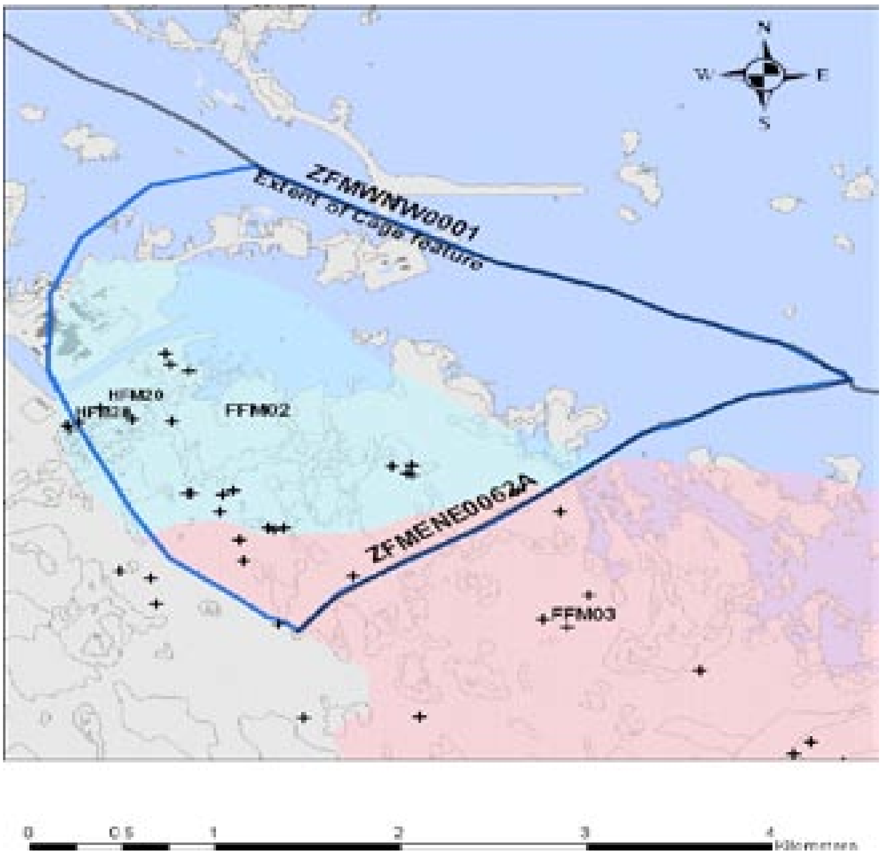


Figure 2-13. *The estimated lateral extent of the bedrock 'aquifer' (referred to in the diagram as the now obsolete 'cage feature' expression) covering the target area /Follin et al. 2007ab/.*

2.3.3 Bedrock features and fracture domains

The geological subdivision of the bedrock at Forsmark into several fracture domains has also been applied to the hydrogeological studies /Follin et al. 2007b/. Early hydrogeological studies had indicated the possible subdivision of the bedrock present between the deformation zones (i.e. excluding the deformation zones) into four sub volumes based on the fracture intensity of flowing fractures, and this concept was tested subsequently by applying the geological criteria already described in section 2.1. This showed that the six fracture domain subdivisions (FFM01-06) are largely in agreement with the earlier four hydrogeological sub-volumes in that the hydrogeological properties of FFM01 are similar to FFM06 and those of FFM03 are similar to FFM04 and FFM05, and therefore consistent with the definition of fracture domains based on geological data.

Table 2-1 /Follin et al. 2007b/ summarises the hydrostructural properties of the different fracture domains.

Table 2-1. Summary of fracture domain properties /Follin et al. 2007b/.

Fracture Domain	**FFM01**			**FFM02**	**FFM03**	
Elevation, m RHB 70	–100 to –200	–200 to –400	–400 to –1,000	–100 to –200	–100 to –400	–400 to –1,000
Intensity of observed open fractures, m^{-1}	1.13	1.02	0.54	3.17	1.10	0.77
Intensity of observed flowing fractures, m^{-1}	0.15	0.04	< 0.01	0.33	0.09	0.05
T_{min}, m^2/s	$2.5 \cdot 10^{-10}$	$2.7 \cdot 10^{-10}$	$6.2 \cdot 10^{-10}$	$2.5 \cdot 10^{-10}$	$1.9 \cdot 10^{-9}$	$1.1 \cdot 10^{-9}$
T_{max}, m^2/s	$4.7 \cdot 10^{-5}$	$1.8 \cdot 10^{-7}$	$8.9 \cdot 10^{-8}$	$7.3 \cdot 10^{-6}$	$6.8 \cdot 10^{-7}$	$1.9 \cdot 10^{-7}$

T = transmissivity

Table 2-1 emphasises clear differences between the fracture domains. In fracture domain FFM02, i.e. the upper 100–200 m of the footwall or target volume (Figure 2-8), the bedrock has a high intensity of open flowing fractures of high transmissivity. It is considered to be hydraulically anisotropic due to a lattice of intersecting near-surface joints and gently dipping single fractures constituting the shallow bedrock aquifer already described in section 2.5.

Fracture domain FFM01, which comprises the major volume of the footwall, thus dominates the target volume (Figure 2-8). It differs from domain FFM02 in that at increased depths there is an overall lower intensity of open, flowing fractures and lower fracture transmissivity. These flowing fractures mostly consist of discrete, subhorizontal to gently dipping single fractures of restricted extent /Follin et al. 2008a/.

Fracture domain FFM03 (Figure 2-8), effectively comprising the hanging wall bedrock (Figure 2-8), shows approximately the same low fracture frequency as FFM01 but contains a significant number of highly transmissive, gently dipping deformation zones. The transmissivity of these zones is high in the upper 400 m and significantly lower below around 500 m, i.e. there is a significant depth trend on the transmissivity data gathered. Flow directions within the candidate area are primarily subhorizontal along the fracture planes towards the north-east with a weak upward component.

The local major steeply dipping deformation zones such as ZFMENE0060A in Figure 2-8 are also subjected to a significant depth trend in transmissivity. However, these steeply dipping zones are also found to be considerably more heterogeneous with both open and sealed flow channels, the former with measurable flow. The vast majority of these steeply dipping zones are parallel with the topographic gradient and transect the candidate area. However, due to the shallow bedrock aquifer and the considerable heterogeneity of these zones that comprise it, it is difficult to generalise the flow pattern. Particle tracking simulations suggest that the flow gradient is predominantly upwards until the shallow bedrock aquifer is reached in the uppermost part of the bedrock /Follin et al. 2008b/.

Fracture domain FFM06 is located in rock domain RFM045 within the target volume (Figure 2-8). It lies beneath fracture domain FFM02 and is closely similar to fracture domain FFM01 hydrogeologically. Geologically, it differs from fracture domain FFM01 by the widespread occurrence of fine-grained and altered (albitised) granitic rock with a higher quartz content /Stephens et al. 2007/.

With respect to the target volume, the overall hydrogeology conforms to that indicated above for the footwall bedrock (i.e. fracture domains FFM01 and FFM02). To illustrate this, Figure 2-14 shows the fracture transmissive data observed at different structural associations in boreholes KFM07A and KFM08A /Olofsson et al. 2007, Figures 6-8 and 6-10/. Borehole KFM07A shows

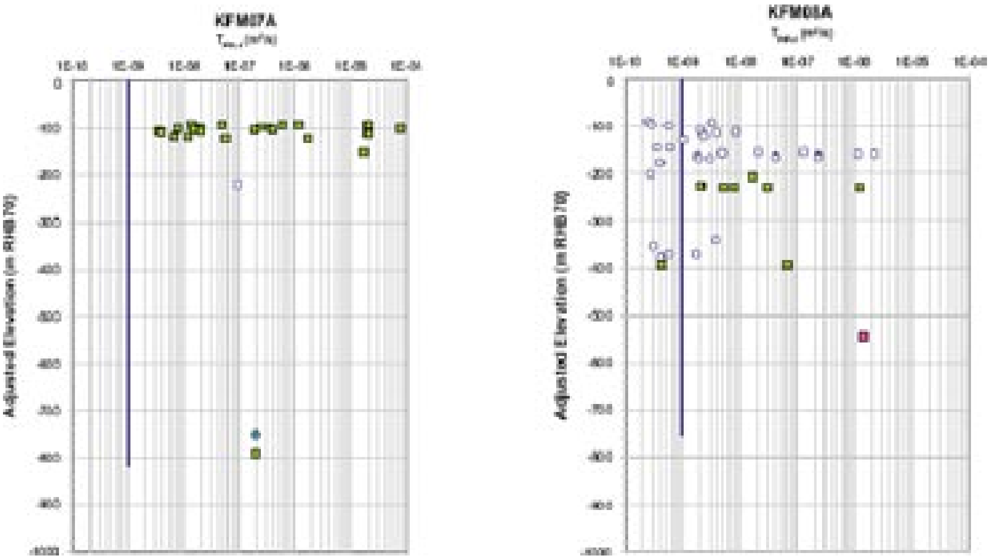


__Figure 2-14.__ PFL-f fracture transmissivity data observed in boreholes KFM07A and KFM08A; the blue line represents the lower threshold of measureable transmissivity at around 1·10^{-9} m^2/s. Coloured symbols represent a deformation zone (green infilled square), possible deformation zone (orange infilled square) and Fracture Domain FFM01 (open circle) /Olofsson et al. 2007, Figures 6-8 and 6-10/.

initial penetration of a shallow zone of variable transmissivity at around –100 m elevation, which corresponds mainly to deformation zone 1203 (Figure 2-7). At greater depths in the footwall bedrock, data are restricted to a single observation at approximately –220 m elevation, representing fracture domain FFM01, to a single observation from outside the target volume at approximately –750 m elevation (representing fracture domain FFM05 but possibly influenced by a nearby deformation zone), and from a deformation zone at approximately –790 m elevation.

Borehole KFM08A penetrates the same deformation zone 1203 as borehole KFM07A, but at greater depth (about –220 to –230 m elevation), and another deformation zone at just under –400 m elevation; a possible deformation zone was located at around –540 m elevation. Otherwise all other observations are restricted to the the footwall bedrock and represent fracture domain FFM01.

2.3.4 Present conditions

Regional scale conceptualisation

Figure 2-15 shows the main regional hydrostructural features of the candidate site and surroundings. The major regional steeply dipping deformation zones of Forsmark (FDZ), Eckarfjärden (EDZ) and Singö (SDZ), which border the candidate area, run perpendicular to the regional groundwater flow direction which is to the east. The steeply dipping deformation zone ENE0060 therefore runs parallel to the regional groundwater flow direction. In the local scale ZFMA2 zone, which is gently dipping to the SE, the groundwater flow is also dominantly to the east /Follin et al. 2007b/.

Although not as well investigated as those structures within the candidate area, the major regional Forsmark, Eckarfjärden and Singö steeply dipping deformation zones are considered to be less important hydraulically than ZFMA2. They probably function as important recharge features both past and present; past evidence of recharge from the last deglaciation can be observed in borehole KFM12A where brackish glacial groundwaters have been collected from quite shallow depths (to around 300 m) within the Forsmark deformation zone.

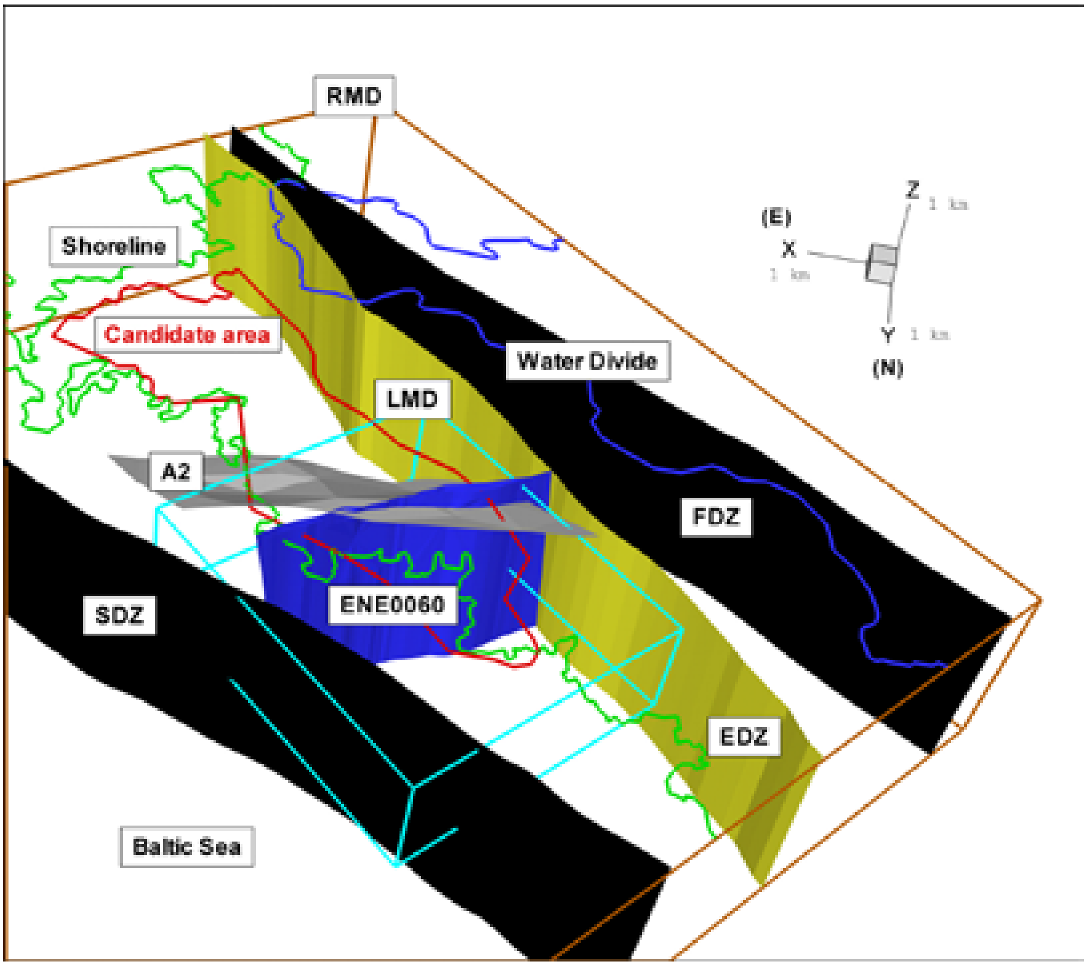


Figure 2-15. The primary hydrogeological characteristics of the Forsmark area. Shown are the candidate area, the regionally significant deformation zones of Forsmark (FDZ), Eckarfjärden (EDZ) and Singö (SDZ) which border the candidate area, and the local major deformation zones A2 and ENE0060. The solid blue line indicates the nearest regional topographical water divide (LMD =, the local model domain; RMD = the south-western part of the regional model domain). After /Follin et al. 2007b/.

Site scale conceptualisation

The conceptual model of present-day hydraulic conditions along a similar NW-SE profile as described from Figure 2-8 (Profile 2) is presented in Figure 2-16 /Follin et al. 2007b/. This figure conveniently summarises the interrelationship between the major gently dipping deformation zones ZFMA2 and ZFMF1 and the series of similarly gently dipping deformation zones of high transmissivity which characterise the hanging wall (i.e. fracture domain FFM03). This contrasts with the footwall bedrock (i.e. fracture domains FFM01 and FFM02) characterised by intensively fractured superficial bedrock (domain FFM02) and very sparsely fractured bedrock below (domain FFM01), representing the target volume (see also Figure 2-9). The former hosts the horizontal sheet joints of high transmissivity (i.e. the shallow bedrock aquiferdescribed in section 2.5) and the latter reflects a sharp decrease in transmissivity, which continues to decrease with increasing depth. As a consequence, the present-day groundwater composition varies within the bedrock depending on the geological structures and their hydraulic properties /Follin et al. 2007b/.

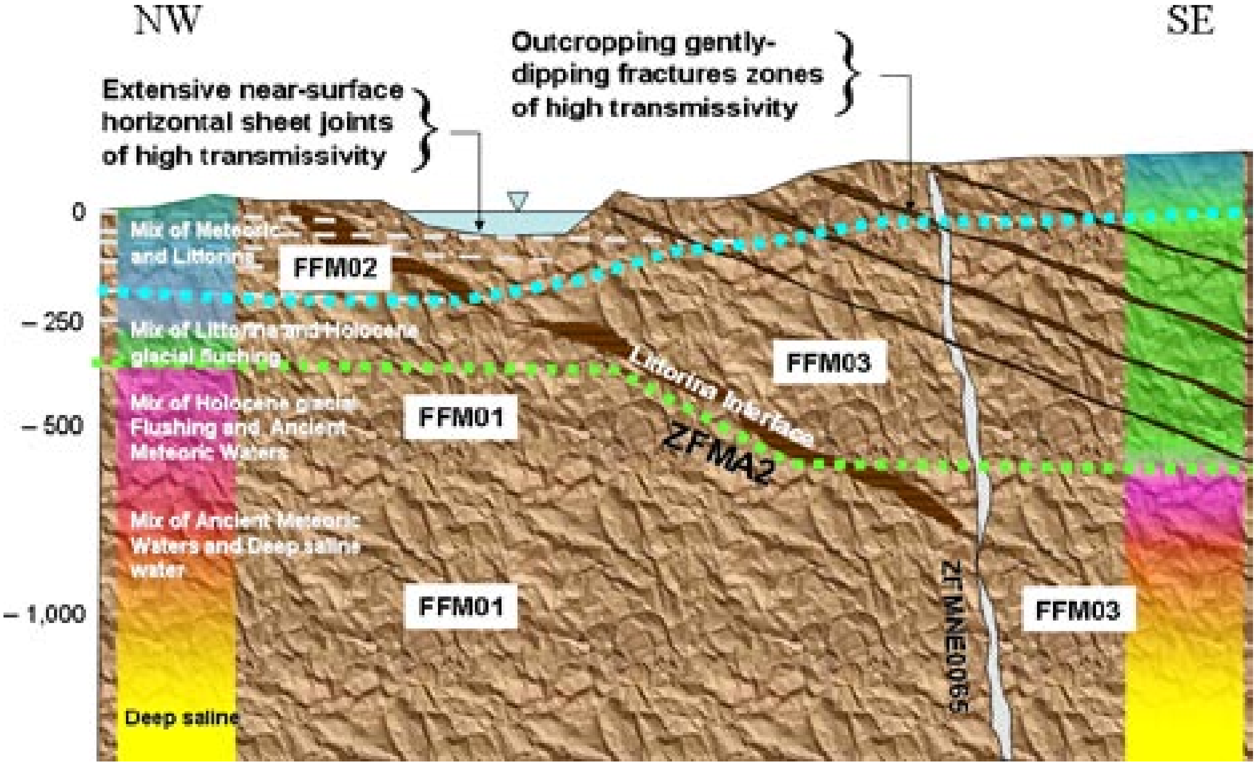


Figure 2-16. Conceptual model for Forsmark illustrating present hydraulic conditions and distribution of the different groundwater types (based on Figure 2-8 cross-section). Fracture domain FFM03 = hanging wall bedrock segment, and fracture domains FFM01 and FFM02 = footwall bedrock segment /Follin et al. 2007b/.

Figure 2-16 also shows the major groundwater types of the area, each reflecting different palaeohydrogeochemical events since the last deglaciation (and beyond). Their depth relationships can be compared in the hanging wall bedrock and the footwall bedrock (i.e. fracture domains FFM01 and FFM02). The most striking difference is the major presence and depth of penetration of Littorina Sea water (maximum salinity lasted between 4500 and 2000 BC) in the hanging wall (to about 600 m) compared to the footwall (to about 300 m), which reflects mainly the difference in scale and transmissivity of the respective water-conducting fracture systems. In addition, the shallow bedrock aquifer in the upper part of the hanging wall has acted both as a hinder to the penetration of the Littorina Sea water and also has facilitated its flushing out following land uplift. Below respectively about 300 m and 600 m depth, transmissivities are low in both the hanging wall and footwall and the groundwater types and their mixtures are generally similar.

Based on /Follin et al. 2007b/ the local scale 2.2 conceptual model was summarised as follows:

1. Glacial meltwater penetrated into the bedrock due to high water pressures below the retreating ice cap. The salinity of the Glacial meltwater was assumed to be close to that of fresh water. At great depths in the bedrock the hydrogeochemical conditions are assumed to be unaffected. The salinity of the deep groundwater was set to ~ 10% TDS by weight at –2,100 m above sea level (‘brine type’ groundwater conditions). Data to support this assumption are based on groundwater samples from the ~ 1,660 m deep borehole KLX02 in Laxemar /SKB 2006a, 2006b/.

2. A density intrusion occurred during the Littorina Sea period (ca 7000–3000 BC) due to a greater salinity at the surface than in the near-surface bedrock groundwater. Probably, the penetration of Littorina Sea water varied depending on the occurrence of geological structures and their hydraulic properties. The greatest penetration occurs in the hanging wall bedrock. A maximum salinity of ~ 1.2% TDS by weight was assumed for the Littorina water.

3. The flushing of the relatively flat and moderately undulating topography within the Forsmark candidate area by Meteoric water probably began ca 900 AD as a result of the ongoing shore level displacement (present-day rate is 6-7 mm/year.) The shore level displacement is a function of two processes – glacial rebound and global sea level changes. The salinity of the Meteoric water was assumed to be close to that of fresh water. The flushing was assumed to be short-circuited by high-transmissive horizontal fractures/sheet joints restricted to the uppermost part of the bedrock (i.e. the shallow bedrock'aquifer' which effectively hinders deeper recharge), thus leaving some fractions of Deep Saline, Glacial water and Littorina Sea water behind.

3 Hydrochemical data

The Forsmark dataset which formed the basis for hydrochemical interpretation and description comprised quality assured field data that were available in the Sicada database at the time of the 2.3 data freeze. These data contain complete hydrochemical analyses including microbes, colloids, gas analysis and porewater analyses from bedrock samples, and are compiled in /Kalinowski (ed) 2008/. The dataset also incorporates versions 1.2 and 2.1 with modifications to some of the data based on outstanding or additional chemical analyses. The groundwater data from other Nordic sites and SFR (Final Repository for Radioactive Operational Waste) have been used for comparison (cf. SKB database Simon).

The objective was to base the Forsmark hydrochemical modelling on the 2.2 data freeze data and to use the 2.3 data freeze and the later extended 2.3 dataset for comparison and as a model check. The use of data and the data versions involved are described here and in /Hallbeck and Pedersen 2008, Gimeno et al. 2008, Waber et al. 2008, Kalinowski (ed) 2008/. Data input for the hydrodynamic modelling group (HydroNet) was based on the 2.2 data with the 2.3 data restricted to strengthening the choice of boundary conditions (i.e. end-member input for hydrodynamic modelling) and to support the development of the conceptual model common to both hydrogeochemistry and hydrogeology.

3.1 Investigated boreholes and groundwater data

3.1.1 Investigated boreholes

The drilled percussion and cored borehole locations are shown in Figure 2-1 but in more detail in Figures 3-1 and 3-2 were each drill site is featured. A total of 25 cored and 38 percussion boreholes have been drilled at 12 drill sites. Of these, cored boreholes KFM04B, KFM07A and KFM09A are located peripheral to the candidate area to the NW, and KFM11A and KFM12A lie outside the candidate area and positioned to investigate the large-scale Singö and Forsmark deformation zones. Seventeen cored boreholes were sampled for hydrochemical evaluation representing locations within, peripheral and outside the candidate area.

Of the 38 percussion boreholes in the Forsmark 2.2/2.3 dataset, 8 are presently included in the monitoring programme, and of the 25 cored boreholes 9 are included in the monitoring programme. Table 3-1 lists the relevant boreholes along with their lengths and vertical depths and also which percussion boreholes have been used as sources of flushing water for drilling the cored boreholes.

3.1.2 Groundwater data

The dataset extracted from Sicada as data freeze 2.2 (October, 2006) and 2.3 (April, 2007), included old data from earlier data freezes and the new data stored up to April 2007. Additional data were included in the ‘Extended 2.3 data freeze’ (October, 2007) from the monitoring programme and three deep boreholes. Table 3-2 summarises the number and type of the samples included in the 2.2-2.3 and the extended 2.3 data freezes.

Figure 3-1. Location of the 12 drill sites within, peripheral and outside the demarcated Forsmark candidate area.

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Figure 3-2. *Details of the 12 drill sites in the Forsmark area, showing the cored boreholes and the accompanying percussion boreholes at each site.*

Table 3-1. Boreholes included in the Forsmark 2.2/2.3 quality control, together with their purpose (percussion) and drilling water source (cored).

Percussion boreholes	Borehole length and vertical depth (m)		Purpose	Cored boreholes	Vertical depth (m)	Drilling water source
	Length	*Vertical*				
HFM01	202.20	195.35	Hy. Hych.	KFM01A	985.40	HFM01
HFM02	100.00	99.91	Hy. Hych.	KFM01B	615.42	HFM01
HFM03	26.00	22.81	Hy. Hych.	KFM01D	996.21	HFM01
HFM04	221.70	214.14	Hy. Hych.	KFM02A	996.45	HFM05
HFM05	200.10	189.91	Hy. Hych.	KFM03A	805.18	HFM06
HFM06	110.70	103.30	Hy. Hych.	KFM04A	832.63	HFM10
HFM08	143.50	135.29	Hy. Hych.	KFM05A	831.57	HFM13
HFM09	50.25	41.32	Geol. Hy. Hych.	KFM06A	785.50	HFM05
HFM10	150.00	134.10	Geol. Hy. Hych.	KFM06C	824.26	HFM05
HFM11	182.35	117.87	Geol. Hy. Hych.	KFM07A	761.88	HFM21
HFM12	209.55	136.59	Geol. Hy. Hych.	KFM08A	750.89	HFM22
HFM13	175.60	146.74	Geol. Hy. Hych.	KFM08D	750.89	HFM22
HFM14	150.50	126.89	Hy. Hych.	KFM09A	625.50	Tap Water
HFM15	99.50	62.42	Geol. Hy. Hych.	KFM09B	476.31	Tap Water
HFM16	132.50	128.54	Geol. Hy. Hych.	KFM10A	342.58	HFM24
HFM17	210.65	207.65	Geol. Hy. Hych.	KFM11A	716.19	HFM33
HFM18	180.75	147.75	Geol. Hy. Hych.	KFM12A	511.93	HFM36
HFM19	182.00	141.46	Geol. Hy. Hych.			
HFM20	301.00	297.58	Hy. Hych.			
HFM21	202.00	153.38	Hy. Hych.			
HFM22	221.00	155.03	Hy. Hych.			
HFM23	211.50	72.90	Hy. Hych.			
HFM24	151.40	129.28	Geol. Hych.			
HFM25	187.50	134.10	Geol. Hych.			
HFM26	202.70	144.08	Geol. Hych.			
HFM27	127.50	115.00	Geol. Hych.			
HFM28	151.20	143.77	Hy. Hych.			
HFM29	199.70	177.91	Geol. Hych.			
HFM32	202.65	198.44	Geol. Hy. Hych.			
HFM33	140.20	110.37	Hy. Hych.			
HFM34	200.75	161.28	Hy. Hych.			
HFM35	200.75	150.42	Hy. Hych.			
HFM36	152.55	110.29	Hy. Hych.			
HFM37	191.75	159.18	Geol. Hych.			
HFM38	200.75	140.68	Geol. Hych.			

Hy. = Hydrology; Hych. = Hydrochemistry; Geol. = Geology

Table 3-2. Number and type of samples included in data freezes 2.2 and 2.3 and the extended 2.3. These include all categories (1-5); cf. Chapter 4 for details.

Type of sample	Number of samples in data freezes F2.2 – 2.3	Extended data freeze F2.3
Percussion boreholes	154	13
Cored boreholes	178	27
Process control	13	
Drilling sample	7	
Tube sampling	65	
Shallow groundwater	317	
Sea water	277	
Lake water	404	
Stream water	398	
Precipitation	31	
Colloids	37	
Microbes	50	
Gas	42	
Rock matrix porewater	52	39

4 Groundwater quality and categorisation

4.1 Background

Assessing groundwater quality and assigning a given category of suitability requires an evaluation of all the available hydrochemical data with reference to known hydraulic conditions in: a) the borehole, b) the fracture zone sections being sampled, and c) the surrounding host bedrock. The reliability of these data is therefore judged as much as possible on prevailing hydraulic and geologic conditions during drilling and subsequent monitoring and sampling. Without the integration of hydrochemistry, geology, hydrogeology and borehole activities there is a great danger that data can be misrepresented.

A strict classification of groundwater samples has been developed and described for the present on-going site investigation studies at Forsmark /SKB 2005/ and Laxemar /SKB 2006ab/. This classification is based on: a) experience of past SKB site investigations /Smellie et al. 1985, Smellie and Laaksoharju 1992/, b) comparison with other national site characterisation programmes /Laaksoharju et al. 1993/, and c) international programmes of natural analogue studies /e.g. Nordstrom et al. 1992, Cramer and Smellie 1994/. In many cases this strictness has been made to meet the demands of, for example, geochemical modelling of water/rock interaction processes (and specialised studies of microbes, colloids and organics) which requires reliable and high quality groundwater data, and this has been largely successful albeit in cases based on few samples of sufficiently high quality. Lower quality samples have resulted mainly from the complex geological and hydrogeological setting of the sites in combination with time constraints in the sampling programme. Because of these reasons, together with newly formulated requirements from the HydroNet and ChemNet modellers, it has been necessary to provide a modified approach to provide a more informative subdivision of intermediate to low quality data. In consequence, this latest Forsmark 2.2/2.3 classification of groundwater samples has been made to satisfy the demands for samples with a less complete set of analyses that nevertheless could be suitable for integration with hydrogeology. This classification, tested to meet HydroNet's requirements, is based on five categories of groundwater quality described in some detail below.

Of the five categories chosen, Categories 1–3 primarily meet the requirements of hydrochemical (but also hydrogeological) modelling, Category 4 may still meet some qualitative hydrochemical requirements (but useful for hydrogeology), and Category 5 may meet some hydrogeological requirements. Category 5 may still be of use for more qualitative hydrogeochemical modelling but needs to be judged with great caution. Note also the specific handling of groundwater data from SFR (Final Repository for Radioactive Operational Waste) situated in the vicinity of the Forsmark site (cf. section 4.2.10).

A colour code has been introduced to quickly distinguish samples when, for example, data are presented in spread-sheet tables or as symbols in scatter plots. Orange is assigned to Category 1, yellow to Category 2, green to Category 3, grey to Category 4 and no colour (i.e. white) to Category 5. In the database the classification category is indicated numerically in a separate column in addition to the colour coding. Details of the classification into the various categories for both the percussion and cored boreholes are presented in Appendix A and Appendix B respectively.

The final selection of data for cored boreholes which best represent the sampled borehole section (i.e. Categories 1 and 2) is based on identifying as near as possible a complete set of major ion and isotope analytical data (particularly tritium, $\delta^{18}O$ and deuterium plus carbon isotopes when available); an acceptable charge balance (± 5%); a low drilling water content < 1–5%, good time-series data coverage, reliable redox values and, if present, a satisfactory coverage of trace element data (including U, Th and other REEs), and dissolved gas, microbe and organic/colloid data.

These high quality data are required, for example, for geochemical equilibrium calculations, modelling of redox conditions, and reliability for specialised studies involving microbes, organics and colloids. On the other hand overall site understanding (e.g. groundwater distribution, origin and evolution and its integration with hydrogeology) is adequately addressed by a combination of all categories with the obvious proviso that the lower the category used, the more caution is required in their interpretation. In such cases the inclusion of high quality data provides an important check or control on data quality and interpretation (Figures 4-1 and 4-2).

The behaviour of chloride (conservative ion) with depth is illustrated in Figure 4-1, where all five categories are plotted. The figure shows that the general trends and important outliers indicated by all data are strengthened and constrained by the higher category samples (1–3), and even some of the Category 4 samples. As expected, the low quality Category 5 samples show the greatest scatter, but even so many follow the major trends. The green rectangle demarcates the extent of the strongest Littorina Sea component, i.e. a narrow range of salinity from about 5,330–5,550 mg/L Cl and within an approximate 130–550 m depth range.

As an example of a less conservative ion, Figure 4-2 shows the distribution of magnesium. Some general trends, once again strengthened by the higher quality data, can be clearly seen: a) low magnesium groundwaters extending from shallow fresh groundwaters to deeper, saline groundwaters, b) Littorina-type brackish groundwaters with higher magnesium (> 140 mg/L) which extend to around 500 m depth (i.e. corresponding to the chloride distribution in Figure 4-1), and c) groundwaters with a weak Littorina Sea component (50–140 mg/L Mg), exemplified by the ringed groundwaters in the figure.

4.2 The hydrochemical dataset and categorisation criteria

This section describes the methodology approach used to categorise the hydrochemical samples compiled in the version F.2.2/2.3 dataset. Additional data sources compiled in the Nordic sites dataset are also included (cf. SKB database Simon).

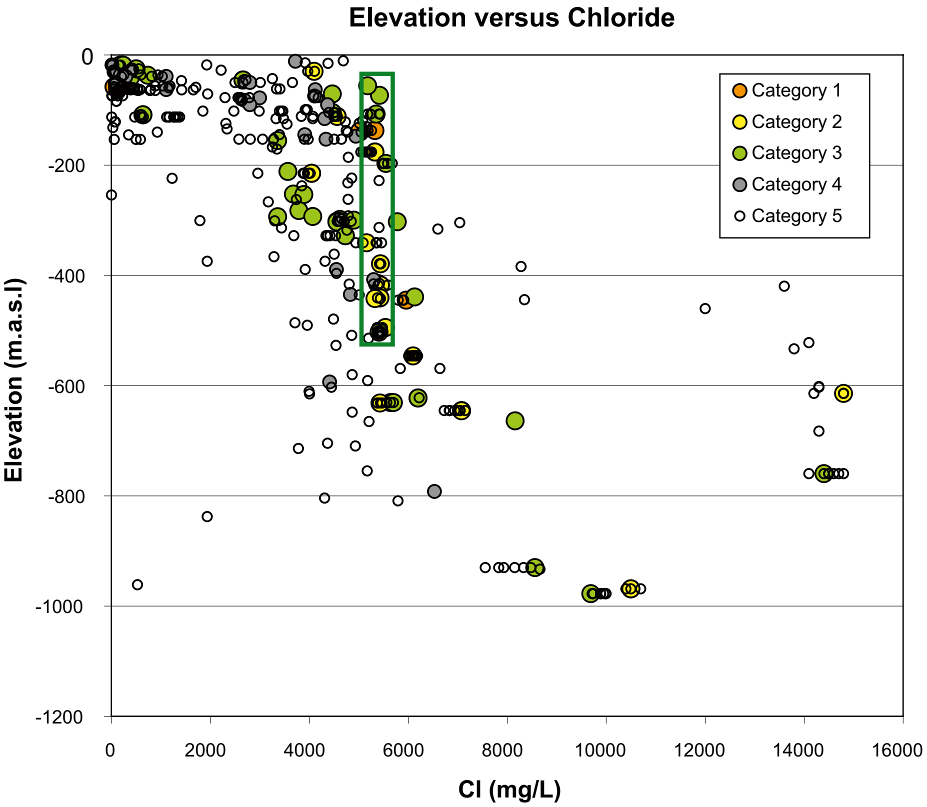

Figure 4-1. *Chloride data versus elevation showing all categories. Green rectangle demarcates the extent of the strongest Littorina Sea component (~ 5,330–5,550 mg/L Cl).*

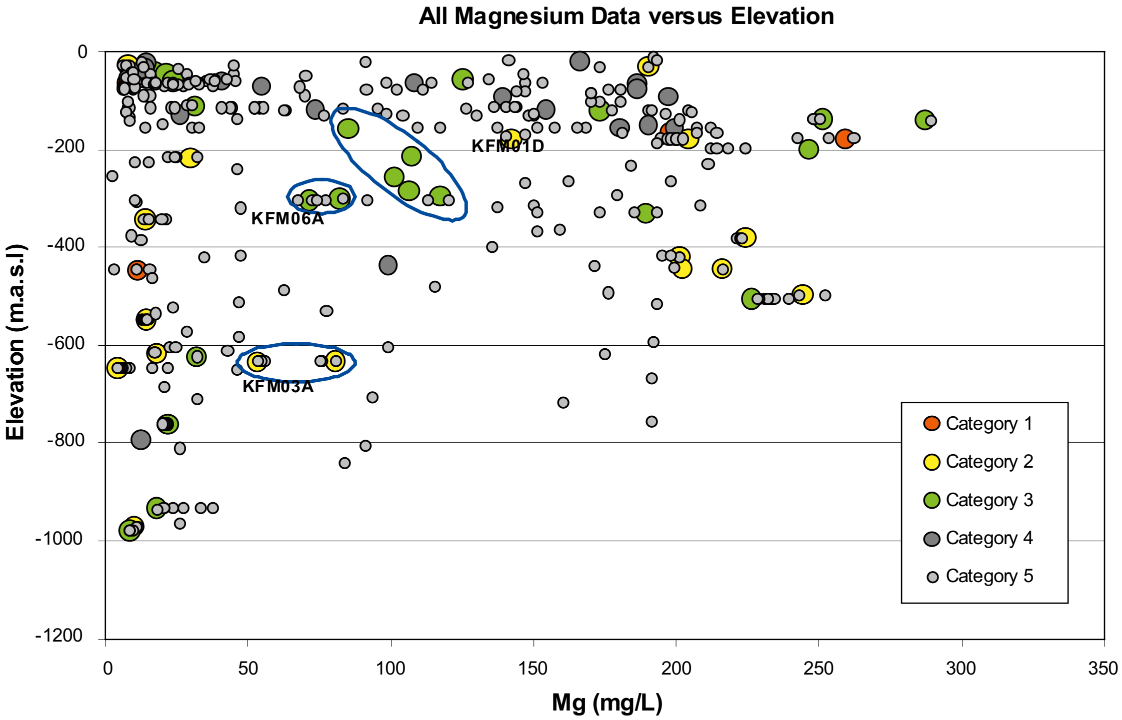

Figure 4-2. *Magnesium data versus elevation showing all categories. Ringed and labelled borehole samples represent a weak Littorina Sea component compared to the higher magnesium-rich samples.*

4.2.1 Cored boreholes

Table 4-1 outlines the approach for judging the groundwater quality categories for cored boreholes (cf. Appendix B for details).

Table 4-1. Classification criteria for cored boreholes.

Cored Boreholes					
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)	x	x	x	x	x
Drilling water (≤ 5%)		x	x	x	x
Drilling water (≤ 10%)			x	x	x
Drilling water (> 10%)				x	x
Time series (adequate)	x	x	x	x	x
Time series (inadequate)			x	x	x
Time series (absent)				x	x
Suitable section length	x	x	x	x	x
Sampling during drilling				x	x
Sampling using hydraulic testing equipment			x	x	x
Tube sampling					x
Charge balance ±5% (±10% for <50 mg/L Cl)	x	x	x	x	x
Major ions (complete)	x	x	x	x	x
Major ions (incomplete)			x	x	x
Environmental isotopes (complete)	x	x	x	x	x
Environmental isotopes (incomplete)		x	x	x	x
Hydraulic effects (short-circuiting)					x

Category 1 Samples: highlighted in orange in the dataset. Characterised by satisfactory time-series data (i.e. stable chemistry recorded over an adequate time period of several days to weeks) and accompanied by complete analytical data (i.e. particularly all major ions and environmental isotopes); a charge balance of ±5%; less or close to 1% drilling water; reliable redox values; a good coverage of trace elements (including U, Th and REEs), and, if possible, microbe, organic and dissolved gas data. Samples with very low HCO_3 content (in the order of < 10 mg/L) do not yield ^{14}C or $\delta^{13}C$ values; if all other parameters are satisfactory, such samples are allocated Category 1.

Category 2 Samples: highlighted in yellow. Of similar quality to Category 1 but marked by incomplete analytical data (usually restricted to an absence of ^{14}C and $\delta^{13}C$ and less trace element, microbe, organic and gas data) and/or with elevated concentrations of drilling water (1–5%).

Category 3 Samples: highlighted in green. This category differs significantly in quality from Categories 1 and 2 in terms of inadequate time-series data; time-series data that indicate instability during sampling; incomplete analytical data (such as absence of some isotopic and trace element data, microbe, organic and gas data, and redox values); elevated drilling water concentrations (5–10%).

Category 4 Samples: highlighted in grey. Samples are mostly restricted to Cl, Br, $\delta^{18}O$, Mg, HCO_3, Na, Ca, SO_4; elevated drilling water concentrations (> 10%); absence or very incomplete time-series data. Type samples are often of an exploratory nature, i.e. mostly taken to see if there is adequate water volume and to check strategic indicators such as drilling water content, salinity (electrical conductivity) ± pH ± major ions (Cl, Br, SO_4, HCO_3) ± $\delta^{18}O$. Some samples taken during drilling also fall within this category.

Category 5 Samples: not highlighted by colour (white). Samples with some major ions or $\delta^{18}O$ missing; no charge balance values; elevated drilling water concentrations (> 10%); absence or very incomplete time-series data. Type samples in this category include those collected during drilling and using the PLU pump test equipment. Samples of Tube Sample origin also fall within this category because of open hole mixing effects. Note however that in some cases the uppermost Tube sample (usually near-surface groundwater from highly transmissive zones) and the deepest sample (usually the most saline accumulation due to density constraints) may be quite representative.

4.2.2 Percussion boreholes

Table 4-2 outlines the approach for judging the groundwater quality categories for cored boreholes (cf. Appendix A for details).

Category 1 Samples: highlighted in orange in the dataset. Based on: a) packed-off borehole sections (i.e. mostly monitoring sections), b) borehole sections were Flow Log data are available to demarcate more specifically the major groundwater input section along the open borehole, and c) isolated borehole sections < 50 m long, where the groundwater data can be related approximately (or precisely) to constrained bedrock levels characterised by dominant water-conducting fracture(s). All cases should be characterised by good time-series data and be accompanied by complete analytical data (i.e. particularly all major ions and environmental isotopes; in most cases a good trace element (including U, Th and other REEs) coverage).

Category 2 Samples: highlighted in yellow. Of similar quality to Category 1 but marked by incomplete analytical data, usually restricted to an absence of ^{14}C and $\delta^{13}C$ and less trace element data.

Category 3 Samples: highlighted in green. Based on: a) borehole sections were Flow Log data are available to demarcate more specifically the major groundwater input section(s) along the open borehole, b) isolated borehole sections < 50 m long were the groundwater data

Table 4-2. Classification criteria for percussion boreholes.

Percussion Boreholes					
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)	x	x	x	x	x
Flow log available		x	x	x	x
Without flow log (0-100m)				x	x
Without flow log (0-200m)					x
Time series/monitoring	x	x	x	x	x
Charge balance ±5% (±10% for <50 mg/L Cl)		x	x	x	x
Major ions (complete)	x	x	x	x	x
Major ions (incomplete)		x	x	x	x
Environmental isotopes (complete)	x	x	x	x	x
Environmental isotopes (incomplete)		x	x	x	x
Monitoring borehole sections	x	x	x	x	x
Hydraulic effects (short-circuiting)					x

can be related approximately (or precisely) to constrained bedrock levels characterised by dominant water-conducting fracture(s), and c) where samples differ significantly in quality from Category 1 and 2 in terms of inadequate time-series data, time-series data that indicate instability during sampling and incomplete analytical data (i.e. mostly absence of some isotopic and trace element data).

Category 4 Samples: highlighted in grey. Based on: a) sampling is restricted to ≤100 m open borehole sections; no Flow Log data available, and b) samples largely similar in quality to Category 3 but restricted to Cl, Br, $\delta^{18}O$, Mg, HCO_3, Na, Ca, SO_4; absence or very incomplete time-series data, often an absence of trace element data.

Category 5 Samples: not highlighted by colour (white). Based on: a) open boreholes lacking Flow Log data such that there is a long section (≥200 m) characterised by groundwater mixing, and b) samples with some major ions or $\delta^{18}O$ missing; often absence of trace element data; no charge balance; absence or very incomplete time-series data.

4.2.3 Private wells, unused dug wells, natural springs and excavated trenches (PFM Near-surface Series Samples)

Quality based on:

- satisfactory charge balance (±10%);
- good coverage of major components (Cl, Br, Mg, HCO_3, Na, Ca, SO_4) and environmental isotopes (tritium, $\delta^{18}O$ and deuterium);
- some trace elements.

Some samples have more complete isotopic data (particularly carbon isotopes). Because of the complex nature of the near-surface environment being sampled, all samples have been highlighted in green.

4.2.4 Shallow soil monitoring pipe data (SFM Series Samples)

Soil pipes have been drilled in different locations: a) to monitor changes in the near-surface groundwater chemistry during percussion and core drilling of nearby deep boreholes, and b) to monitor the natural undisturbed near-surface groundwater system. An attempt was made to choose early or 'First-Strike' samples provided that there was no recorded major contamination with soil particles. The following criteria were chosen:

- satisfactory charge balance (± 10%);
- good coverage of major components (Cl, Br, Mg, HCO_3, Na, Ca, SO_4);
- suitable coverage of environmental isotopes (tritium, $\delta^{18}O$ and deuterium ± carbon isotopes);
- some trace element data.

Because of the complex nature of the near-surface environment being sampled, all the samples meeting the above conditions have been highlighted in green.

Of importance are data relating to seasonal changes over a period of months to years. Therefore, when a time-series of samples from the same campaign are available from a single location, all samples are considered for final evaluation if the analytical data listed above are complete. When only a single sample is available, it is recommended to be used with caution since the chemistry is inadequate to indicate whether there is any seasonal fluctuation or not.

4.2.5 Baltic Sea water samples (Seawater PFM Series)

A large number of samples have been collected over a period of approximately 24 months ranging from the open Baltic Sea, to coastal areas comprising bays and coves, some of which border active freshwater drainage discharge areas of varying importance. From a hydrochemical viewpoint, the important selection criteria are:

- Representative Baltic Sea end member for the Forsmark area latitude which has not been influenced by freshwater discharge; samples taken at increasing depths are also included.
- Representative compositions from coastal Baltic Sea localities which may be in hydraulic contact at depth with the mainland where deep boreholes are located.

The selection of waters considered to be suitably close to a Baltic Sea end member for this latitude have been based on the charge balance (±5%), chloride content within the range of 2,500–2,800 mg/L and a complete set of environmental isotopes of tritium, $\delta^{18}O$, and deuterium (highlighted in green in the Forsmark 2.2/2.3database). Samples restricted only to major ion analytical data also have been recommended for use (highlighted in pink).

4.2.6 Lake and stream water samples (Lake and Stream Water PFM Series)

Surface lake and stream water samples have been evaluated based on charge balance (±10%) and the presence of major ions and isotopic data. In common with some of the soil pipe groundwaters, these surface waters may have been subject to seasonal fluctuations, complex reaction processes in the biosphere and potential discharge influences. Consequently, in the absence of knowing what could be representative or not, all selected samples that conform to the above criteria are recommended at this juncture (highlighted in green in the Forsmark 2.2/2.3 database). Samples restricted only to major ion analytical data also have been recommended for use (highlighted in pink).

4.2.7 Precipitation PFM Series

Thirty samples are included, collected during an approx. four year period. These waters have not undergone any quality check *senso stricto*. On the other hand, the main intention has been to monitor $\delta^{18}O$, $\delta^{2}H$ and tritium, since these parameters are used to identify modern meteoric groundwater components at depth. Disturbances, such as unpredictable annual and seasonal trends and possible evaporation, have not been evaluated in this present quality check.

Because of the difficulty of assessing representativeness, suitable samples with isotopic values and adequate major ion data are highlighted in green in the Forsmark 2.2/2.3 data base.

4.2.8 Rock porewaters

Drillcore samples from boreholes KFM01D, KFM02B, KFM06A, KFM08B and KFM09C have been sampled for porewater studies. These are not listed in the Forsmark 2.2/2.3 dataset but are available from the Sicada database and described in /Waber et al. 2008/. These data are not included in the dataset since assessment is based on criteria which differ from those used for the groundwaters. For example, rock porewater quality may be influenced by several variables, for example rock stress, experimental artefacts and the uncertainty associated with analysis of small water volumes (around 5 mL).

4.2.9 Nordic sites

Hydrogeochemical evaluation of the Forsmark may benefit from comparison with other Fennoscandian sites, in particular Olkiluoto but also Laxemar, Simpevarp, Äspö, Ävrö and Oskarshamn. Groundwater data from all these sites are compiled in the 'Nordic Table' and these data also have been evaluated with respect to their suitability. This was carried out in parallel to the evaluation of the Simpevarp v. 1.2 data /SKB 2004/ and Forsmark v. 1.2 data /SKB 2005/ and also involved earlier evaluations /e.g. Smellie and Laaksoharju 1992, Laaksoharju et al. 1995, Pitkänen et al. 1999, 2004/. The modified evaluation into 5 categories has not been carried out at these Nordic sites.

4.2.10 SFR data

Data from SFR (Final Repository for Radioactive Operational Waste) originate from the vicinity of the repository which is located underground some 60 metres offshore at a depth of 50 m and connected by a tunnel to the site of the Forsmark nuclear power plant. The sampled boreholes are located to intersect important deformation and fracture zones bounding the repository such that the groundwater samples form part of a control system to monitor long-term changes in chemistry. The groundwaters are collected under natural pressure conditions (i.e. no pumping) and no analysis have been carried out for drilling water content, although it is unlikely that any drilling water that may have been used has survived to the present day. These SFR groundwater samples therefore cannot be evaluated using the same criteria as used for the Forsmark cored borehole groundwaters.

All SFR samples have been allocated Category 5 status although some information from the major elements and $\delta^{18}O/\delta D$ can be informative. Based on the sampling date, the samples have been labelled generally as representing initial (prior to excavation 1988) and transition (after 1989 to the present day) conditions, respectively, with transition conditions reflecting SFR repository drift and/or pre-closure conditions. Most of the analyses cover only the major elements and environmental isotopes. The bromide values need to be used with caution due to large uncertainties and it is recommended that the tritium values from these boreholes are not used at all. With very few exceptions all tritium values are high, even those associated with groundwaters of Littorina type.

In terms of general information, Figure 4-3 shows the relationship between magnesium and chloride. Despite the general mixing that has, and is occurring, overall the Littorina-type groundwaters (initial and transitional) fall within the 5,000–6,000 mg/L Cl range and are ringed in green, and typical Baltic Sea waters (both initial and present) in blue. Between these 'end-members' mixing is widespread. There is also an indication of a brackish non-marine component (i.e. low in magnesium and ringed in red) which probably corresponds to the Old Meteoric ± Old Glacial ± Last Deglaciation + Saline member which existed prior to the Littorina Sea transgression (see Chapters 6 and 7 for discussion).

Figure 4-4 shows the variation of $\delta^{18}O$ with chloride where enriched $\delta^{18}O$ values (–10 to –8‰ SMOW) characterise the marine waters (Baltic and Littorina), separated only by their respective chloride contents. The slightly lower $\delta^{18}O$ values for the most typical Littorina waters compared with present Baltic Sea, are in contrast to expected values for a pure marine water with higher salinity (like the Littorina). This supports mixing of Littorina with a glacial meltwater that lowered the $\delta^{18}O$ significantly.

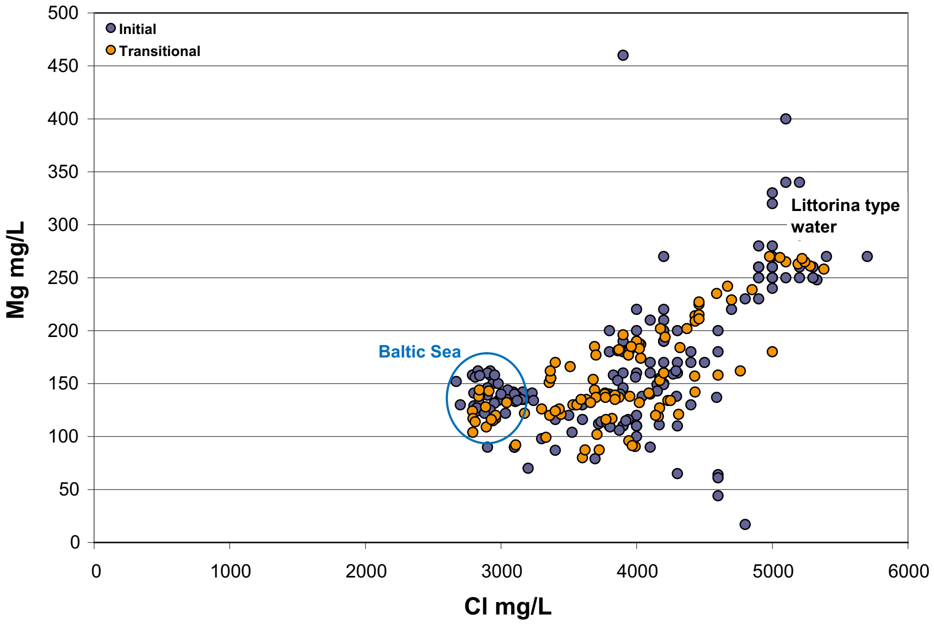

Figure 4-3. *Magnesium versus chloride for all SFR samples. The Baltic Sea and Littorina type end members are indicated with an area of mixing in between.*

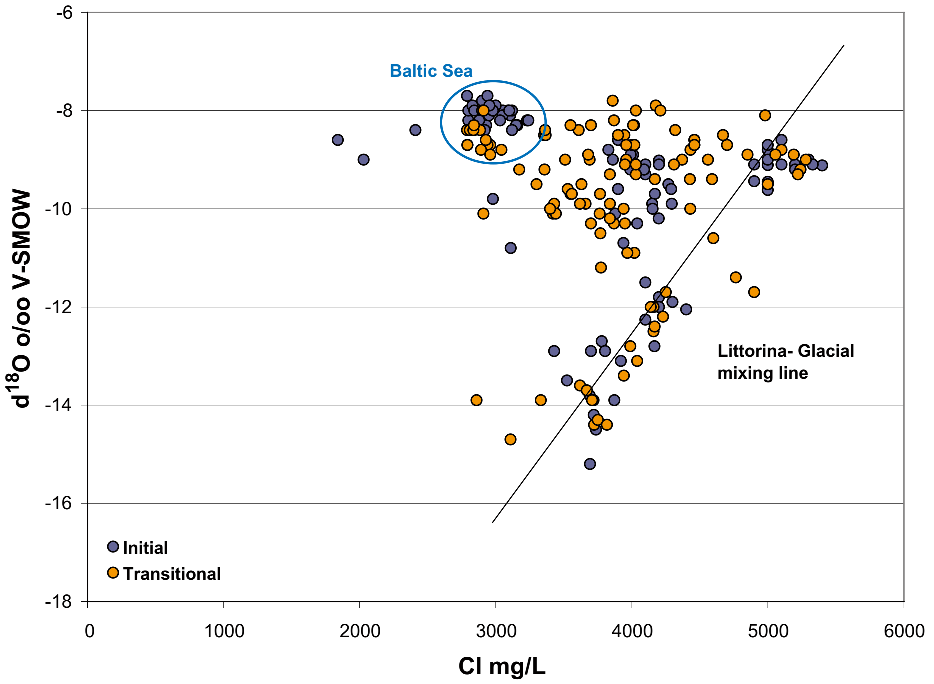

Figure 4-4. *Chloride versus $\delta^{18}O$ for all SFR samples. Apparent is the mixing of a Littorina-type groundwater with a depleted $\delta^{18}O$ groundwater member. Forsmark 2.2/2.3 quality assessment.*

4.3 Issues impacting on groundwater quality

This section focuses on specific issues which can impact directly on the quality of the groundwaters sampled.

4.3.1 Flushing or drilling water impact

A major consideration in evaluating the quality of the hydrochemical samples is the potential impact of flushing or drilling water on the chemistry of the collected samples. Historically at SKB, a maximum of 1% drilling water (based on the amount of uranine tracer) has been used to indicate samples of the highest quality. The choice of the drilling water source is therefore of great importance because the greater the difference in composition the greater the impact of unwanted contamination. For example, near-surface groundwater used as a source of drilling water may be similar in composition to formation groundwaters sampled for hydrochemical characterisation from the upper part of a cored borehole section. Although the presence of uranine will indicate drilling water contamination, its impact on the formation groundwater chemistry will be minimal. Contrastingly, mixing of the same drilling water with more saline groundwaters at depth will result in dilution (equals contamination) if large amounts are present.

Brackish drilling waters of higher salinity (e.g. Littorina origin) have been used in the drilling of some boreholes (e.g. KFM06A) where it resulted in significant contamination of non-marine groundwaters of similar salinity along the borehole (see section 4.3.4).

Drilling water sources from percussion drilled boreholes in the vicinity of a planned drilling site are initially screened, ideally to provide a groundwater of similar composition and redox properties to that expected in the bedrock during drilling. Because the maximum depth of the percussion boreholes is around 200 m, the drilling water source is often a fresh meteoric recharge water (< 200 mg/L Cl) but, depending on the drilling location, groundwaters of greater salinity may be present close to the surface and therefore in more extreme cases brackish Littorina-type groundwaters have been used for drilling (e.g. for borehole KFM06A). The redox potential of the drilling water can be ensured by pre-storing the drilling water under reducing conditions (N_2 atmosphere), and sterilising it using an in-line ultra violet radiation unit to remove surface-derived contaminating bacteria /Pedersen 2005a/. The uranine solution used to spike the drilling water is also sterilised.

Irrespective of the drilling water source chosen, however, there will always be a difference at some stage during drilling between the chemistry of the drilling water source and the chemistry of the formation groundwater in the bedrock being drilled. It is therefore essential to know the full major and trace ion and isotope chemistry of the drilling water prior to use so that its impact can be assessed quantitatively.

4.3.2 Hydrogeological impact

In addition to hydrochemical considerations there are important surrounding issues that also have to be evaluated in parallel. For example:

- A groundwater may indicate a Category 1 or 2 but the time-series data may indicate chemical instability throughout the sampling period. This poses the question of which composition, if any, most closely represents this borehole section. In this particular case a Category 1 or 2 is not valid and a lower category choice is made.
- When possible, the category choice is usually based on a stabilised groundwater composition, but it may have been preceded by an initial increase (or decrease) in salinity, such that the initial samples in the time series are certainly not representative, but all of the later stabilised samples may be. The established stability thus gives added confidence to the category selected.

- During sampling, fracture networks intersecting the boreholes may lead to short-circuiting of the groundwater flow in the surrounding bedrock and also to bypassing the packer systems used to isolate the borehole sections being sampled. This effectively means that the section sampled may have been supplied by mixed groundwaters from higher or lower levels in the bedrock, and/or mixed borehole waters above or below the packer systems. In both cases the sampled groundwaters when interpreted in isolation may be evaluated erroneously as being of high quality.

These three examples are critical in quality evaluation, for example, short-circuiting may have had an influence in cases (a) and (b). The final category decision in such cases is based therefore on a combination of hydrological input (e.g. differential flow measurements; injection tests etc) and expert judgement based on existing hydrochemical knowledge of the borehole in question (i.e. chemical comparison with higher or lower levels) and the site (i.e. what compositional range would be expected at the depth of sampling) (see section 4.3.4).

4.3.3 Groundwater flow log data

The use of flow log data to identify specific borehole sections with a dominating groundwater inflow(s), helped considerably in the hydrochemical categorisation of several percussion boreholes, therefore increasing their value to better understand the groundwater chemistry and its distribution in the upper 0–200 m of the bedrock (Figures 4-5 and 4-6). Integration with the known hydrogeology was also critical, for example, the influence of the shallow bedrock aquifer on groundwater flow patterns and mixing close to the bedrock surface (0–60 m) in the footwall bedrock segment (i.e. fracture domains FFM01 and FFM02).

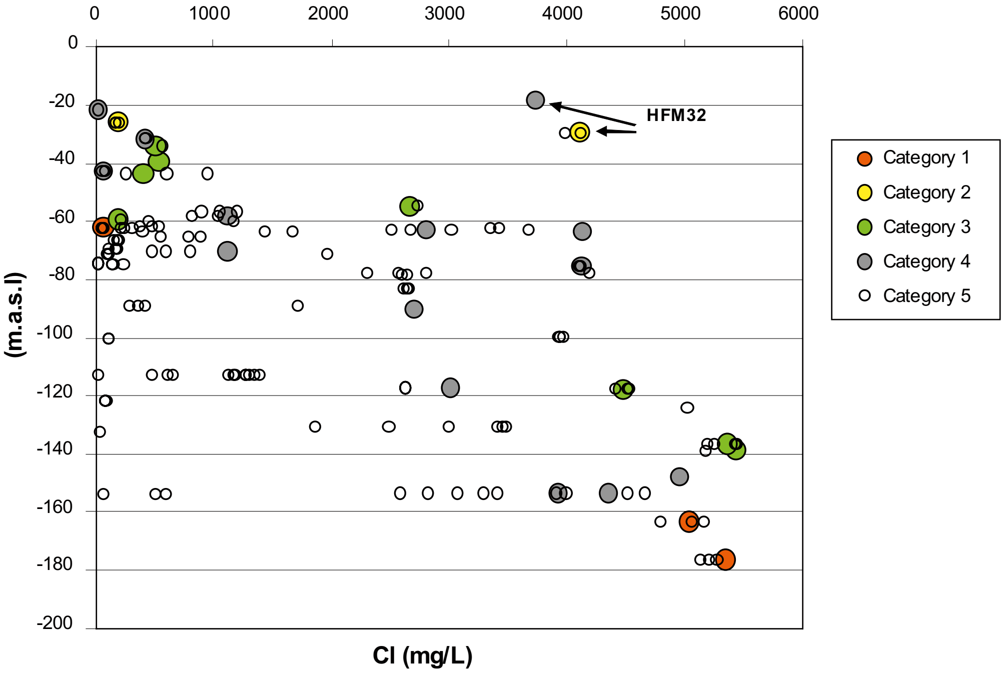

Figure 4-5. *Cl versus elevation for the percussion boreholes showing the upper ~ 60 m to be distinguished by groundwaters of low salinity (< 500 mg/L Cl) and the 60–180 m interval with groundwaters increasingly becoming more brackish with depth. Samples from HFM32 (indicated), situated in lake Bolundsfjärden, are anomalous with Littorina-type groundwaters locally discharging close to the surface.*

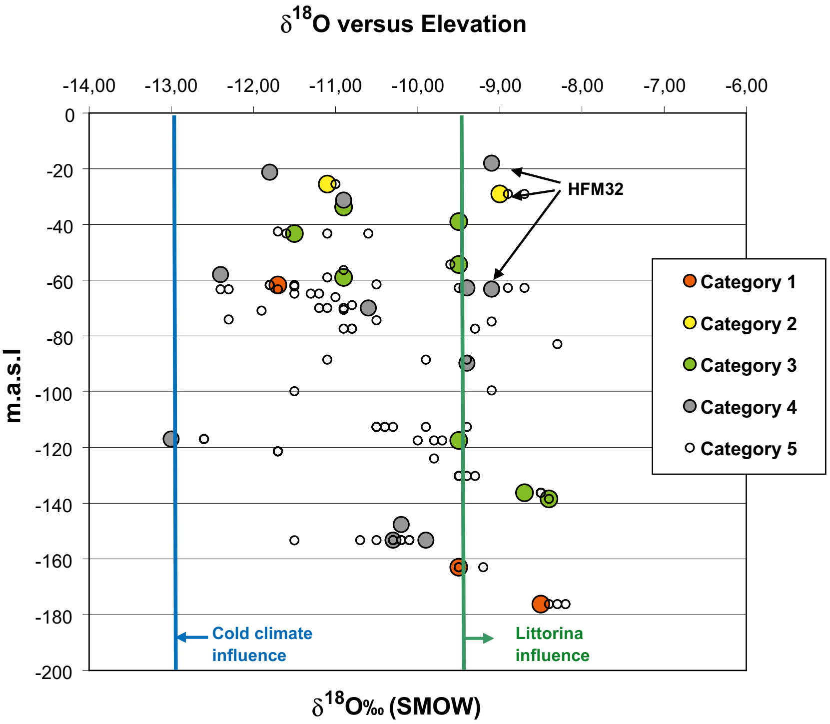

Figure 4-6. *$\delta^{18}O$ versus elevation for the percussion boreholes distinguishing groundwaters influenced by recharge, glacial input and Littorina.*

Based on Category 1-3 samples, Figure 4-5 shows a clear division between fresh and low saline groundwaters (< 500 mg/L Cl) down to around 60 m, and increasingly more brackish groundwaters (2,500–5,500 mg/L Cl) within the 60–180 m interval. Borehole HFM32 is anomalous in that it represents an area of near-surface brackish marine (Littorina) type groundwater locally discharging under Lake Bolundsfjärden.

Figure 4-6 shows the $\delta^{18}O$ distribution with elevation for the percussion boreholes. The average recharge $\delta^{18}O$ range is taken to be –12.5 to –9.5‰ V-SMOW, and most values plot within this interval. Outside the recharge range one depleted $\delta^{18}O$ value indicates a cold climate component; enriched $\delta^{18}O$ values relate mostly to strong brackish marine (Littorina) type groundwaters from HFM19, 32 and 33, located in the hanging wall bedrock segment.

Table 4-3 gives a breakdown of the various categories for the percussion boreholes together with an indication of those boreholes presently included in the long-term monitoring programme and those for which there are documented flow log input data in the F.2.2/2.3 dataset.

4.3.4 Cored boreholes

Cored borehole sampled section lengths, mid-point vertical elevation of the sections, and the groundwater categories, are given in Table 4-4.

Generally, quality evaluation of the cored boreholes is initially assessed by considering the borehole location with respect to the geology and the motivation behind the drilling. In most cases the boreholes sampled are hydrochemically prioritised, but sampling has also been carried out in other boreholes where the prime objectives have been to gain structural and hydrogeological information. In these latter cases, the quality of the groundwater might be expected to be of lower quality due to a range of downhole activities (e.g. geophysical logging; hydraulic injection tests etc) which have preceded the hydrochemical sampling. In addition, short-circuiting may occur during hydrochemical sampling where large-scale deformation structures have been penetrated.

Table 4-3. Percussion Boreholes: Vertical elevation mid-points of sampled sections and evaluated groundwater quality category. (Blue raster represents long-term monitoring sections; Italics indicate available Flow Log measurement data).

Percussion Borehole	Section Mid-Point; Vertical Elevation	Groundwater Category	Percussion Borehole	Section Mid-Point; Vertical Elevation	Groundwater Category
HFM01	*36.50*	*3*	*HFM18*	*30.90*	*4*
HFM01	112.68	5	*HFM19*	*137.10*	*1*
HFM01	131.97	5	HFM20	153.32	5
HFM02	*39.91*	*3*	HFM21	102.20	5
HFM02	59.64	5	*HFM22*	*50.00*	*4*
HFM03	*18.10*	*4*	HFM23	66.11	5
HFM04	*57.91*	*1*	HFM24	61.48	5
HFM04	121.42	5	*HFM24*	*25.10*	*3*
HFM05	*144.60*	*4*	HFM25	70.91	5
HFM05	*144.60*	*4*	HFM26	74.37	5
HFM06	*63.00*	*4*	*HFM27*	*45.60*	*3*
HFM08	*82.40*	*4*	HFM27	56.38	5
HFM08	*130.40*	*3*	HFM28	70.65	5
HFM09	*18.50*	*2*	HFM29	84.10	5
HFM10	*104.60*	*3*	*HFM32*	*18.00*	*4*
HFM11	63.27	5	*HFM32*	*30.00*	*2*
HFM12	*78.00*	*4*	HFM32	63.24	4
HFM13	77.38	5	HFM32	99.53	5
HFM13	*140.00*	*1*	HFM32	124.02	5
HFM14	62.22	5	HFM32	147.68	4
HFM14	64.86	5	*HFM33*	*107.50*	*3*
HFM15	59.05	5	HFM34	82.92	5
HFM15	?	5	HFM35	78.24	5
HFM16	*57.19*	*3*	*HFM36*	*39.00*	*4*
HFM16	68.93	5	HFM37	74.10	5
HFM17	*27.40*	*4*	*HFM38*	*74.85*	*4*

The next stage is to locate the sampling points (initially based on downhole PLU differential flow measurements) on the geological single-hole interpretation profiles which show, in addition to the different bedrock types, the frequency, nature and importance of the sampled fracture zones intersected during drilling. The orientation of these fracture/sampling points on a 2D plane, and sometimes 3D as shown for borehole KFM02A in Figure 4-7, provide the opportunity to determine qualitatively the possibility of major network interconnections in the bedrock surrounding the borehole which might contribute to short-circuiting during hydrochemical pumping/sampling.

Based on this geological background, use is made of the downhole transmissivity measurements and electrical conductivity logs to try and understand how the borehole reacts hydraulically: a) during drilling, b) during flushing and clearing the borehole (if carried out), and c) during open-hole conditions where groundwater circulation and mixing can last for several weeks to months prior to sampling. Unfortunately no water budget information was available, apart from drilling water loss, in order to more quantitatively estimate open-hole effects. In the absence of such hydraulic data, use has been made of the electrical conductivity logs together with the transmissivity measurements. To underline the importance of understanding the behaviour of the boreholes to each of the downhole activities carried out in them, the following example from KFM06A is described.

Table 4-4. Cored Boreholes: Vertical elevation mid-points, borehole lengths of sampled sections and evaluated groundwater quality category. (Blue raster represents long-term monitoring).

Cored Borehole	Sampled Section Borehole Length (m)	Section Mid-Point: Vertical Elevation (m)	Groundwater Category
KFM01A	110.10-120.77	111.75	2
KFM01A	109.00-130.00	115.79	4
KFM01A	176.80-183.90	176.27	2
KFM01B	34.74-46.24	36.61	4
KFM01D	194.00-195.00	155.69	3
KFM01D	263.80-264.80	211.45	3
KFM01D	314.50-319.50	253.31	3
KFM01D	354.90-355.90	282.32	3
KFM01D	369.00-370.00	293.12	3
KFM01D	428.50-435.64	340.87	2
KFM01D	568.00-575.14	445.17	1
KFM02A	18.00-100.40	51.67	4
KFM02A	106.50-126.50	108.86	3
KFM02A	411.00-442.00	417.80	2
KFM02A	490.00-518.00	494.97	2
KFM02A	509.00-516.08	503.34	3
KFM03A	386.00-391.00	379.06	2
KFM03A	448.50-453.00	440.79	2
KFM03A	448.50-455.62	442.35	2
KFM03A	633.50-650.00	631.10	2
KFM03A	639.00-646.12	631.91	2
KFM03A	803.20-804.20	792.11	4
KFM03A	939.50-946.62	930.50	3
KFM03A	969.50-994.50	969.14	2
KFM03A	980.00-1001.19	977.67	3
KFM04A	230.50-237.64	197.00	3
KFM05A	100.00-121.60	90.41	4
KFM06A	0.00-100.30	39.37	4
KFM06A	341.00-362.00	298.54	3
KFM06A	353.50-360.62	301.99	3
KFM06A	738.00-748.00	622.78	3
KFM06A	768.00-775.12	645.34	2
KFM06C	531.00-540.00	434.84	4
KFM06C	647.00-666.00	527.04	5
KFM07A	848.00-1001.55	759.72	3
KFM08A	100.00-203.51	127.33	4
KFM08A	683.50-690.64	546.42	2
KFM09A	785.10-792.24	614.21	2
KFM10A	298.00-305.14	214.77	2
KFM10A	430.00-440.00	299.83	3
KFM10A	478.00-487.49	328.08	3
KFM11A	447.50-454.64	389.68	4
KFM11A	690.00-710.00	593.76	4
KFM12A	343.00-363.00	293.64	3
KFM12A	516.00-536.00	439.26	3

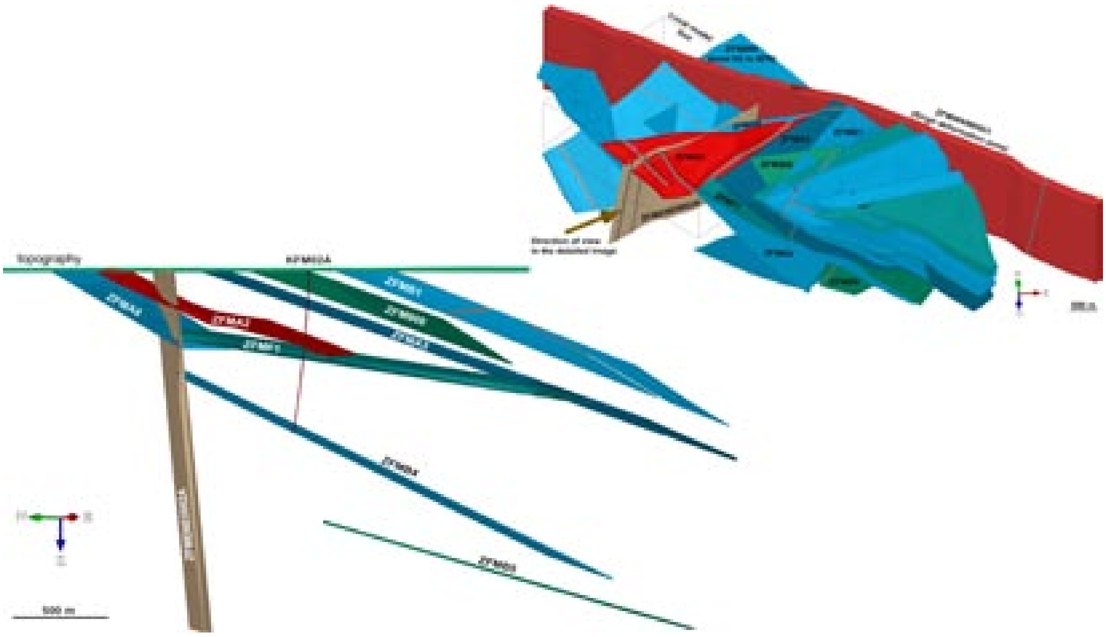

Figure 4-7. Cutting plane in 3-D showing the orientation and dip of a series of gently dipping deformation zones intercepted by borehole KFM02A /Stephens et al. 2007, Figure 5-15/.

Borehole KFM06A was drilled to a length of 1,000.64 m (vertical depth 831.37 m) at an inclination of 60° to the horizontal. The drilling water source was HFM05 with an average composition during drilling of Cl = 3,170 mg/L, Mg = 144 mg/L and Tritium = 4.6 TU (i.e. mainly a mixture of young, near-surface groundwater and older groundwater of Littorina-type). It was chosen because of the low concentration of total organic carbon (< 5% mg/L). The uranine tracer budget (i.e. drilling water in versus drilling water out) suggested that approximately 400 m^3 of the drilling water was lost to the borehole and the adjacent host bedrock during drilling /Berg et al. 2005/. Some of the measurements carried out in Borehole KFM06A during differential flow logging /Rouhiainen and Sokolnicki 2005/ are discussed below and shown in Figure 4-8.

The flow rates measured with and without pumping within 5 metre sections along the borehole (Figure 4-8a) show responses which reflect the transmissivity of the borehole. These are particularly marked between 100–400 m borehole length (0–100 m is cased and could not be measured) and sporadically at approximately 450 m, 620–660 m and 740–770 m borehole length. By integrating this information with the single hole geological interpretation profiles, these borehole lengths correspond to transmissivities ranging from below detection at < 10^{-9} to $10^{-4.8}$ m^2/s (section 100–400 m which intersects two major steeply dipping deformation zones ZFM60B/60A), < 10^{-9} m^2/s (sections at 450 m and 620–680 m corresponding to deformation zones ZFM73 and ZFM25/61) and $10^{-7.8}$–$10^{-6.7}$ m^2/s (section 740–777 m; minor fracture zone).

Without pumping the flow measurements show that the upper approximately 100–270 m borehole length indicates 'natural' flow from the bedrock into the borehole, and conversely for borehole lengths 300–400 m and around 745 m. One measurement at 770 m borehole length indicates flow into the borehole. Pumping the sections shows flow from all sections into the borehole. Open hole static conditions, following drilling and other downhole activities prior to hydrochemical sampling, should therefore encourage formation groundwaters from different sources/levels to enter the borehole and mix with the residual mixed water types already present in the borehole. This will be especially marked along the 100–300 m length where flow rates between 200–800 Lh^{-1} (most at 500 Lh^{-1}) have been measured during the differential flow logging. To a lesser extent, borehole waters of mixed origin may migrate into the bedrock, notably between 300-400 m, where flow rates of 30 Lh^{-1} have been recorded.

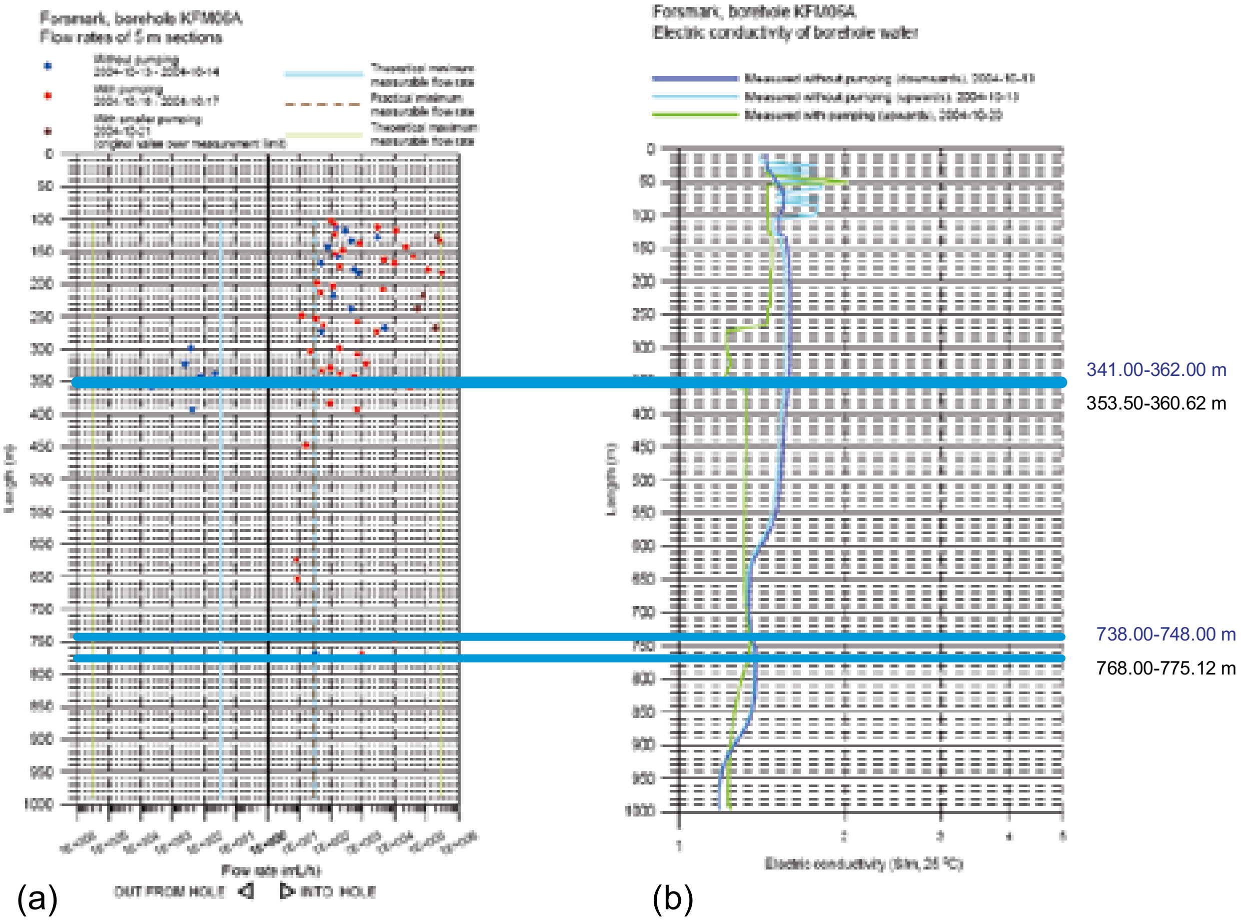

Figure 4-8. *Borehole KFM06A: Differential flow measurements /Rouhiainen and Sokolnicki 2005/ showing: a) the groundwater flow rates and directions related to the borehole and the host bedrock, and b) the open-hole electrical conductivity log. The groundwater sampling locations are marked with blue lines and labelled in black font; those labelled in blue font are long-term monitoring sections.*

Based on this open hole behaviour, drilling under high water pressure coupled with the moderate to high transmissivities measured in the upper 400 m of the borehole, and bearing in mind that 400m^3 drilling water was lost to the bedrock, all selected borehole sections for groundwater sampling would be expected to contain a component of drilling water. This is supported by the residual drilling water component found in all sampled groundwaters (ranging from 1.55–10.80%), even allowing for the initial cleaning of the borehole and the continuous pumping over many days associated with the sampling campaign. The deeper section at 768.00–775.12 m (Figure 4-8a) showed a gradual decrease from 10.80–1.55% after a period of 45 days. This substantial period of time underlines the extent of the drilling water contamination in the sampled fracture zone, but also indicates that the fracture is reasonably well constrained (i.e. not interconnected with other fractures or fracture networks), such that most of the drilling water contamination has been removed successfully. (However, non-representative groundwaters from higher or lower bedrock levels via interconnected fracture systems cannot be ruled out completely after such a long pumping period.) In contrast, the upper 100–300 m is characterised by an increase in fracture frequency, probably contributing to interconnections between fractures and fracture zones, and high transmissivity. This combination certainly has contributed to considerable drilling water contamination under high drilling pressures, and the fracture network has probably acted both as a major reservoir for the lost drilling water and also facilitated mixing with formation groundwaters. A large reservoir of mixing is indicated by the homogeneity of the collected groundwater samples from section 353.50–360.62 m over a period of 24 days /Berg et al. 2005/. These samples also showed little variation in drilling water which remained constant within the range of 6.65–8.00%.

Figure 4-8b shows the open-hole logs of the electrical conductivity (EC) measurements for borehole KFM06A, measured both with and without pumping. Without pumping, i.e. static open-hole conditions, the EC shows average values around 1.6 s/m down to approx. 600 m, after which there is an irregular decrease to around 1.3 S/m at the hole bottom. This higher salinity to approximately 600 m probably results from groundwaters of greater salinity (i.e. groundwaters originating from the series of highly transmissive sections extending down to approximately 300 m) entering into and moving down along the borehole. Movement downhole will be largely density driven and the extent will depend on the density of the groundwater mixture already in the borehole. The decrease in salinity from 600 m towards the bottom of the borehole is due to a high content of less saline drilling water, measured at 60–70% /Berg et al. 2005/.

As a result of pumping there is a general decrease in EC to around 1.4 S m^{-1} extending down to approximately 600 m (where the EC indicates similar salinities to the water mixture in the hole bottom prior to pumping), but particularly from 270–360 m (to around 1.25–1.30 S/m). This latter decrease coincides with the deformation zone which indicated flow from the borehole into the bedrock under static (non-pumping) conditions (Figure 4-8a).

During drilling, therefore, various amounts of drilling water under high pressure have been introduced into the moderate to high transmissive zones extending down to around 360 m, and subsequently partly removed during EC logging associated with pumping. This is particularly evident at the 270–360 m borehole length interval. Overall, these observations are supported by comparing the known salinity of the drilling water introduced into this fracture system (around 3,000 mg/L Cl, ~ 1 S/m), with that subsequently recorded from the formation groundwaters sampled from the 353.50–360.62 m section (around 4,600 mg/L Cl, ~1.3–1.4 S/m /Berg et al. 2005/. Some dilution of the formation groundwaters has occurred, and this dilution factor still persists after sampling. That the true higher salinity of the formation groundwaters may not have been achieved during sampling is suggested from the EC log (and hydrochemical logging /Berg 2005/) which shows that the greatest salinity measured in the open borehole at 1.6–1.7 S/m would be equivalent to around 5,600 mg/L Cl. However, as discussed above, this EC value probably relates more to the transmissive zones down to around 300 m, rather than to the section sampled below at 353.50–360.62 m, and represents groundwaters of Littorina origin with salinities averaging around 5,500 mg/L Cl.

In conclusion, the history of drilling and groundwater sampling of borehole KFM06A underlines the potential difficulties encountered in assessing the quality of the sampled groundwaters, and the necessity to integrate borehole activities with borehole hydraulics and geology to more quantitatively evaluate the quality of the samples.

4.3.5 Monitoring boreholes

Monitoring sections which constitute the ‘Hydro Monitoring Programme’ are also sampled as part of the ‘Hydrochemical Monitoring Programme’ (see Tables 4-3 and 4-4). In Forsmark sampling of monitoring sections was initiated in June 2005; since then the number of sections sampled has increased in parallel with expansion of the site investigations to a total of 17 in the F. 2.2/2.3 dataset. Eight sections are located in percussion boreholes and 9 in cored boreholes. These sections are important in that they extend the time-series data for some of the earlier drilled borehole sampling locations. However, some problems became apparent during the quality evaluation: a) the presence of contamination resulting from hydraulic monitoring programme, and b) the instability of the groundwater chemistry in some of the monitored sections. As also discussed above in section 3.14, for the best possible comparison of monitoring data with the originally performed groundwater sampling for chemical characterisation (CCC samples), it is important that the sections sampled are from almost identical depths although this is seldom the case. In most cases, however, the correspondence is acceptable, but needs always to be checked.

4.3.6 Contamination from hydraulic tracer tests

Some issues of concern could be linked to the hydraulic tracer test programme which involved at different stages the injection of uranine (and additionally caesium in one test). In some of the groundwaters sampled within the hydrochemical programme this has resulted in an increase of uranine which may be incorrectly interpreted as an artefact of the introduced uranine during initial drilling of the boreholes. Furthermore, in two of the monitoring samples there are anomalous increases in caesium.

Three hydraulic activities (see below) were carried out in selected borehole sections. Activity (a) 'Borehole Probe Dilution Test (natural gradient)', was conducted to select suitable sections to carry out the Swiw (Single Well Injection and Withdrawl) tests, i.e. activity (b). Subsequently, activity (c) 'Dilution Tests (natural gradient)',was carried out in selected sections on an annual basis, and these tests will be continued into the future.

Dilution measurements were used to determine hydraulic flow under a natural gradient using the SKB dilution probe in approximately 5–10 sections per borehole from boreholes KFM01A, KFM02A, KFM03A, KFM04A and KFM06A. This entailed injecting uranine tracer (concentration about 1 mg) into the packed-off borehole sections followed by monitoring the dispersion of uranine over a period of 1–10 days per section. This was followed by removal of the equipment and no pumping was carried out to remove excess uranine still remaining in the packed-off section. Residual uranine may therefore be present in the fractures intersecting the borehole section monitored.

Based on (a), Swiw (Single Well Injection and Withdrawl) tests were carried out using the SKB dilution probe in boreholes KFM02A (414.7–417.7 m) and KFM03A (643.5–644.5 m). The objective was to determine transport properties of groundwater flow paths in fractures/fracture zones in a depth range of 300–700 m at transmissivities of 1×10^{-8}–1×10^{-6} m^2/s. Initially, the background uranine content was measured in the formation groundwater. This was followed by injecting clean formation groundwater to maintain steady state conditions with respect to pressure and flow prior to injecting tracers of uranine (0.5–1g) and absorbing Cs (1–3g). After injection, the section was once again rinsed with clean formation groundwater and pumping was conducted for 1–3 weeks to force the tracers out into the host bedrock and to monitor their behaviour; recovery of uranine was over 90% and Cs between 30–70%. In common with activity (a) this was followed by removal of the equipment and no pumping was carried out to remove potential excesses of uranine and Cs still remaining in the packed-off section. Residual uranine and Cs may therefore be present in the fractures intersecting the borehole section monitored.

(c) Dilution measurements have been carried out also in several boreholes in a maximum of two sections per borehole. This entailed injecting uranine (15–50 mg/section) via a circulation cell into selected sections in boreholes KFM02A (411–442 and 490–518 m), KFM03A (633.5–650.0 m and 969.5–994.5 m) and KFM06A (341–362 m and 738–748 m), and percussion boreholes HFM02 (38–48 m), HFM04 (58–66 m), HFM13 (159–173 m), HFM15 (85–95 m), HFM19 (168–182 m) and HFM32 (26–31 m). Dilution under natural flow conditions was monitored for approximately 5 days. In common with activities (a) and (b) this was followed by removal of the equipment and no pumping was carried out to remove any excess uranine still remaining in the packed-off section. Residual uranine may therefore be present in the fractures intersecting the borehole section monitored.

The use of uranine is unfortunate in these tracer tests as the same tracer is also used to estimate the amount of drilling water contamination that has entered into some of the hydrochemical samples during drilling, and therefore its presence plays an important role in the evaluation of sample quality. However, some of the background uranine values were measured prior to tracer injection and these are listed below in Table 4-5, together with values following the tests, and detailed information on the various monitoring tests carried out in the borehole sections /Berg and Nilsson 2007/.

Table 4-5. Investigations/activities in the cored boreholes that might affect the quality of collected groundwater samples.

Borehole [Idcode]	Section [m]	Time period [yymmdd]	Activity[1]	Comment	Initial/background Uranine conc. (mg/L)	Final Uranine conc. (mg/L)
KFM01A	117.7-118.8	041106 to 041108	HY215[2]	Injection of Uranine (0.0013 g), ~1.36 mg/L if the section volume is considered.	0.14 (uncertain)	1.2
	109.0-130.0	050620 to 050712	HY212, HY210[3]	0.0092 g Uranine injected, total volume of injected fluid 1.8205x10^{-5} m^{3}.	-	-
	109.0-130.0	50712	HY231[4]	Injection of high amounts, ~20 g, Uranine due to tracer test.	-	-
	109.0-130.0	050818 to 050819	Pumping[4]	Attempt to reduce Uranine content from HY231 after completed tracer test.	-	-
KFM02A	414.7-417.7	050214 to 050302	HY215,	Natural gradient test, injection of Uranine (0.0020 g) up to ~0.75 mg/L considering section volume.	0.05	0.7
			HY214[2]	SWIW-test, 1.04 g Uranine and 1.03 g Cesium was added to the section. Total injected volume of tracer fluid 1.140x10-2 m3.	0.014	0.031
				Rubidium is not used.	Cs 4.35 µg/L	Cs 74.1µg/L
	411.0-442.0	051116 to 051122	HY212[3]	0.0241 g Uranine injected, total volume of injected fluid 4.862x10^{-5} m^{3}.	-	-
	411.0-442.0	060627 to 060711	HY212, HY210[5]	0.0196 g Uranine injected, total volume of injected fluid 4.225x10^{-5} m^{3}.	-	-
KFM02A	511.5-514.5	050302 to 050304	HY215[2]	Injection of Uranine (0.0004 g), ~0.15 mg/L if the section volume is considered.	0.01	0.04
	490.0-518.0	051122 to 051128	HY212[3]	0.0252 g Uranine injected, total volume of injected fluid 5.085x10^{-5} m^{3}.	-	-
	490.0-518.0	060630 to 060707	HY212, HY210[5]	0.0209 g Uranine injected, total volume of injected fluid 4.511x10^{-5} m^{3}.	-	-
KFM03A	643.5-644.5	041214 to 041216	HY215[2]	Injection of Uranine (0.0015), ~1.22 mg/L if the section volume is considered.	0.04	0.8
	643.5-644.5	050107 to 050117	HY214[2]	SWIW-test, 0.949 g Uranine and 1.03 g Cesium was added to the section. Total injected volume of tracer fluid 1.013x10^{-2} m^{3}.	0.008	0.132
				Rubidium is not used.	Cs 1.81 µg/L	Cs 157 µg/L
	633.5-650.0	051118 to 051123	HY212[3]	0.0244 g Uranine injected, total volume of injected fluid 4.920x10^{-5} m^{3}.	-	-
KFM03A	986.0-987.0	041119 to 041123	HY215[2]	Injection of Uranine (0.0025 g), ~2.48 mg/L if the section volume is considered.	0.04	2.3
	969.5-994.5	051123 to 051205	HY212[3]	0.0330 g Uranine injected, total volume of injected fluid 6.660x10^{-5} m^{3}.	-	-
KFM06A	341.0-362.0	051117 to 051124	HY212[3]	0.0175 g Uranine injected, total volume of injected fluid 3.520x10^{-5} m^{3}.	-	-
	341.0-362.0	060626 to 060711	HY212, HY210[5]	0.0156 g Uranine injected, total volume of injected fluid 3.377x10^{-5} m^{3}.	-	-
KFM06A	738.0-748.0	051124 to 051205	HY212[5]	0.0253 g Uranine injected, total volume of injected fluid 5.100x10^{-5} m^{3}.	-	-
	738.0-748.0	060630 to 0607007	HY212, HY210[5]	0.0233 g Uranine injected, total volume of injected fluid 5.040x10^{-5} m^{3}.	-	-

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[1] HY215 = Borehole probe dilution test, natural gradient, HY212 = Dilution test natural gradient, HY210 = Dilution test stressed gradient, HY231 = Tracer injection during tracer tests, HY214 = SWIW-test.

[2] /P-05-77/

[3] /P-06-59/

[4] /P-06-125/

[5] /P-06-188/

In addition, its use has also contributed to some additional contamination since it is not 100% pure. One percent of impurities are present which comprise mostly Rb (50 ppm), Al, Ba, Si and Fe (2–9 ppm) with more minor amounts of Cr, Cu, Pb, Li, Mg, Mn and Ni (< 1 ppm). Furthermore, residual drilling water contamination and possibly the raising and lowering of some of the downhole equipment may also have contributed to some anomalous trace element values including Al, Fe, As, Zn, Ni, Mo and Cr etc (cf. section 5.2). Contamination from the use of the tracer Cs in activity (b) is clearly shown in Figure 4-9.

4.3.7 Groundwater chemical instability

It has been stressed earlier that groundwater samples should be taken when the groundwater records time-series stability, i.e. a levelling out of monitored parameters such as pH, electrical conductivity, temperature and uranine (i.e. drilling fluid) over an acceptable period of time. This is routine practice for CCC (Complete Chemical Characterisation) sampling, but not for the monitoring sampling. For this type of sampling the section volume is pumped to allow an equivalent of three section volumes to be removed. The groundwater is considered then to be representative of the bedrock fracture groundwaters and subsequently sampled. As sampling in some monitoring sections has just commenced, there may be only one sample available for evaluation; in other cases involving older sections, sampling has been carried out over a two year period with sampling approximately twice a year.

The data show that long-term stability in some of the sections, for some of the elements, has not been achieved, and for such samples there is therefore a degree of uncertainty to their quality. Figures 4-10 and 4-11 show the behaviour of selected elements and $\delta^{18}O$ from the monitoring programme. These time-series plots show changes in composition to varying degrees and illustrate the chemical and isotopic sensitivity during monitoring. In part, these observations indicate that groundwater stability has not been achieved. This may either reflect the natural evolution of the groundwater chemistry with time, i.e. adjusting to more natural conditions following downhole perturbation activities, or due to the influence of the sampling procedures (e.g. the observed variation in uranium). In terms of data quality, most of the unstable monitored sections would certainly benefit from additional time-series data prior to sampling.

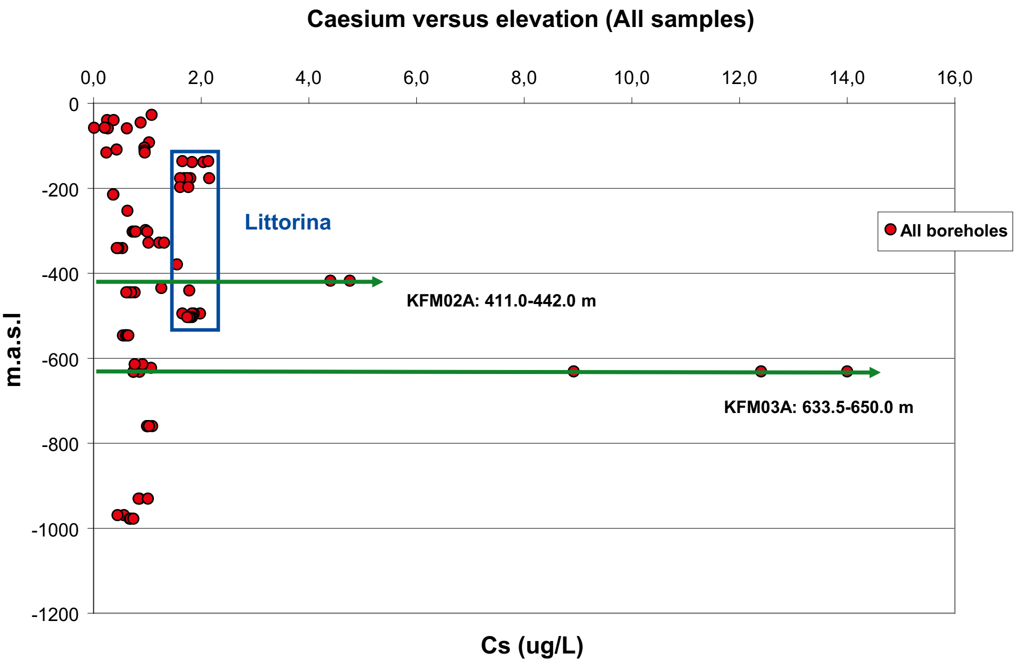


Figure 4-9. Plot of caesium versus elevation showing clearly the two anomalous sections (green arrows) contaminated in boreholes KFM02A and KFM03A. Note also the small but significant increase in caesium above background associated with the Littorina-type brackish groundwaters.

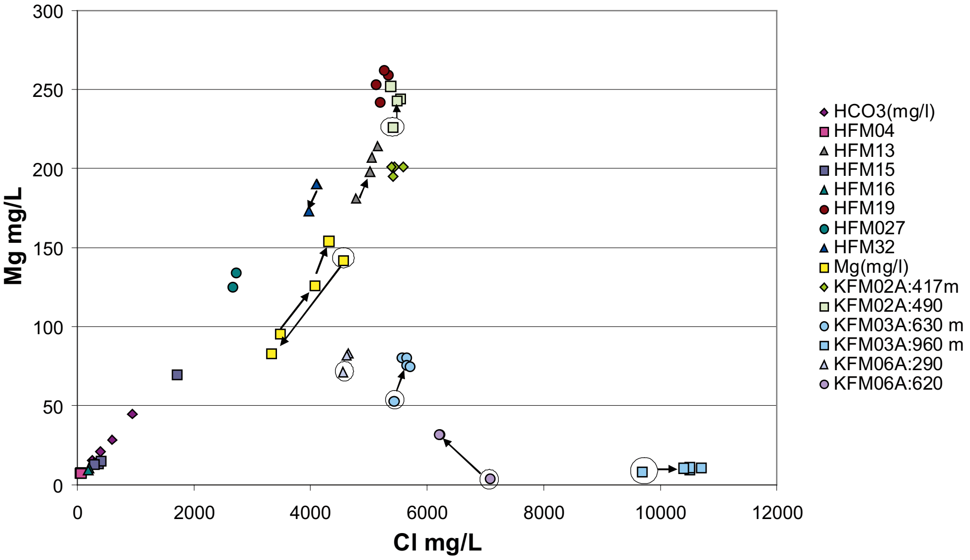


Figure 4-10. *Magnesium versus chloride for monitored percussion and cored boreholes. Ringed samples represent initial (CCC) results.*

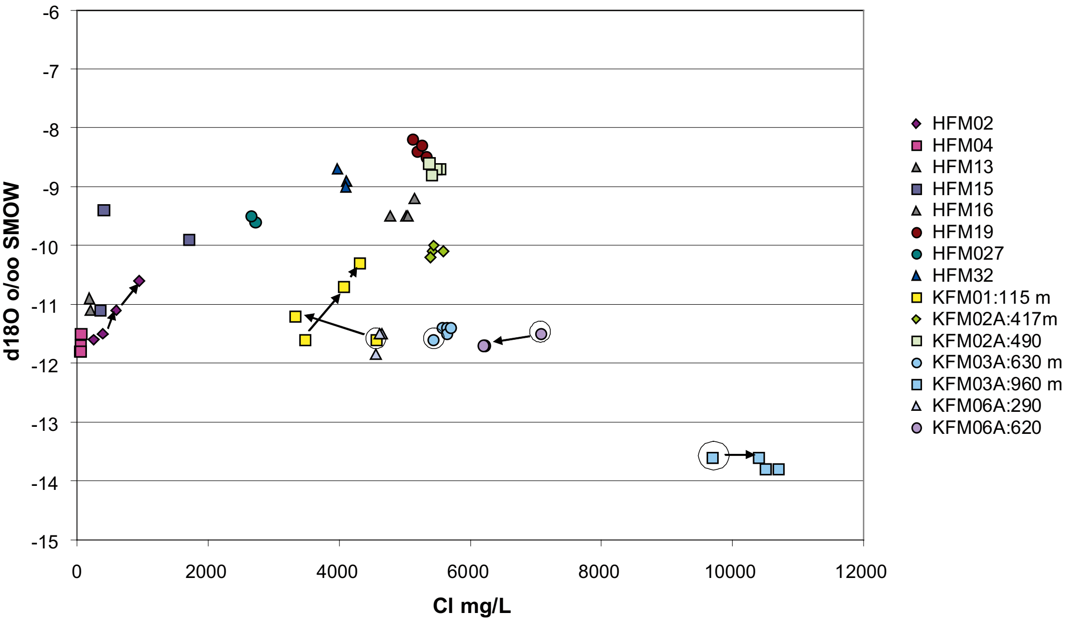


Figure 4-11. *$\delta^{18}O$ versus chloride for monitored percussion and cored boreholes. Ringed samples represent initial (CCC) results.*

Recent sampling from some of the monitoring boreholes shows steady increases in several elements including uranium (A-Ch. Nilsson 2008, per. comm.). This is disturbing and underlines the necessity to take an adequate time-series sequence of samples to determine whether such increases are due to borehole perturbation immediately prior to sampling. If so, then further sampling would reveal whether this increase is real or an anthropogenic pulse which would decrease and settle given adequate time.

4.3.8 The tritium problem

Low but detectable tritium contents (around one or a few TU) have been detected in brackish and saline groundwaters from intermediate depth at Forsmark. These types of groundwaters, brackish marine and brackish to saline non-marine, are usually tritium-free and therefore the risk of artificial contamination needs to be addressed.

The tritium contents in the brackish and saline groundwaters do not correlate with the amount of drilling fluid; furthermore the drilling water used is usually low in tritium. Possible additional tritium sources are surface and modern Baltic Sea waters. Precipitation has tritium contents within the range 7.4 to 15.1 TU and modern Baltic Sea water shows slightly higher values (10.3 to 19.3 TU). It has also been observed that occasionally high values can be produced by the nearby nuclear power plant were up to 120 TU have been measured in the Baltic Sea water close to the outlet of the cooling water canal despite large dilution effects (A-Ch. Nilsson, 2007, per. comm.). In addition, one high value (750 TU) has been measured in a water sample collected from one of the pumping stations at SFR (the Storage for Low and Medium level waste bordering the Forsmark site).

Two other possible direct risks of tritium contamination are: 1) The water used in the pumping equipment during CCC sampling contains deionised water produced at the power plant. This has been tested for tritium once and showed low values; however the possibility of contamination can not be completely ruled out. 2) Problems with high background levels in the laboratory may be a problem. This is, however, contradicted by the presence of tritium-free (> 0.8 TU) samples measured in waters from all sample batches.

In situ production of tritium is another possibility. This was addressed during the investigations at the Stripa mine during the 1980s by /Andrews et al. 1989a/ who demonstrated that the maximum in situ production of tritium at Stripa is close to detection limit (< 0.7 TU). In situ production at Forsmark can be assumed to be even lower since the Stripa host rock is more enriched in uranium.

From Figures 4-12 and 4-13 it is obvious that most of the waters with chloride contents higher than 6,000 mg/L have tritium values below detection limit. The very high values of 41 TU in a tube sample from borehole KFM03A is therefore surprising and indicates some type of contamination.

Figure 4-14 shows tritium versus chloride for the samples from the last update (2007-11-30). It is evident that the number of samples with chloride contents in the range 5,000 to 11,000 mg/L that have detectable tritium contents have increased over the last 4 years, i.e. since the site investigation programme commenced. No correlation with the drilling fluid content can explain these tritium contents.

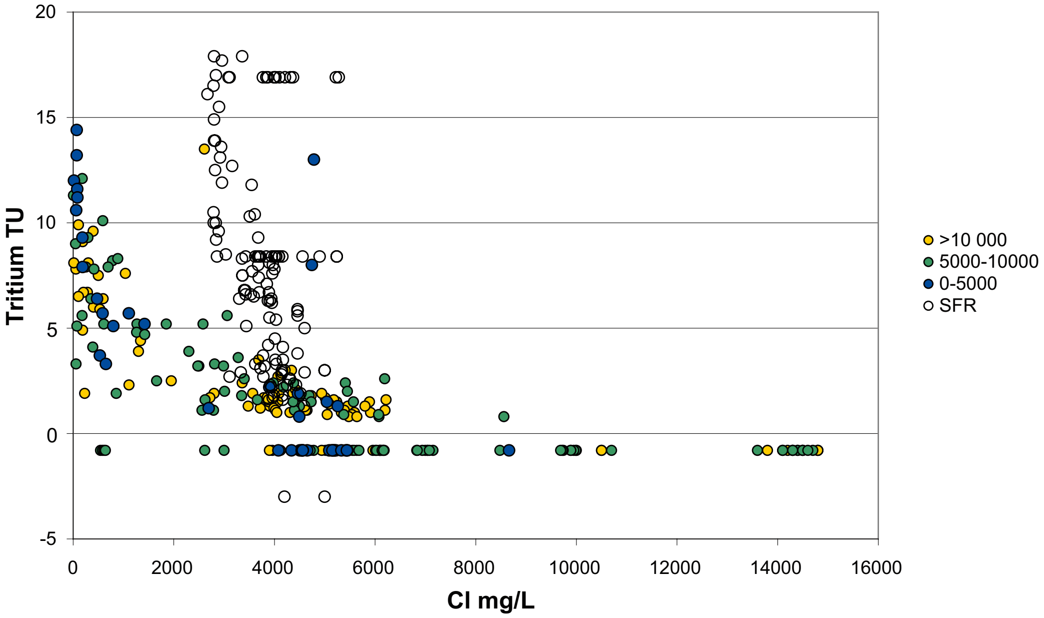


***Figure 4-12.** Groundwater samples with drilling contents less than 10% have been plotted versus Cl content. The samples have been divided based on their sample number in an attempt to reveal a possible evolution over time. The highest numbers (> 10,000) are the most recent samples whereas sample numbers < 5,000 represent the results from the first years of the site investigation) (source: F2.2-2.3 data set).*

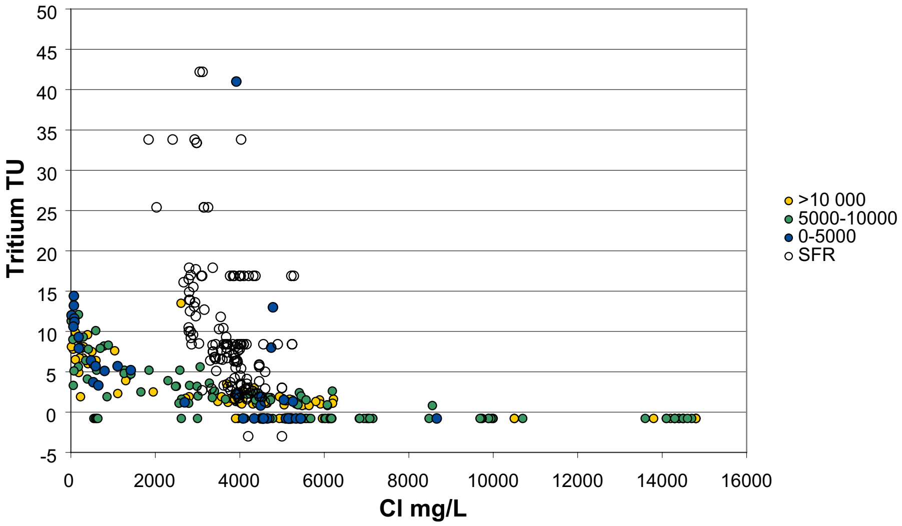


***Figure 4-13.** Groundwater samples with drilling contents less than 10% have been plotted versus Cl content. The samples have been divided based on their sample number in an attempt to reveal a possible evolution over time. The highest numbers (> 10,000) are the most recent samples whereas sample numbers < 5,000 represent results from the first years of the site investigation) source F2.2-2.3 data set). Same diagram as Figure 4-12 but different scale to include the high tritium contents from SFR (mostly from the 1990s) but also one very high value from the site investigation i.e. (tube sampling in KFM03A).*

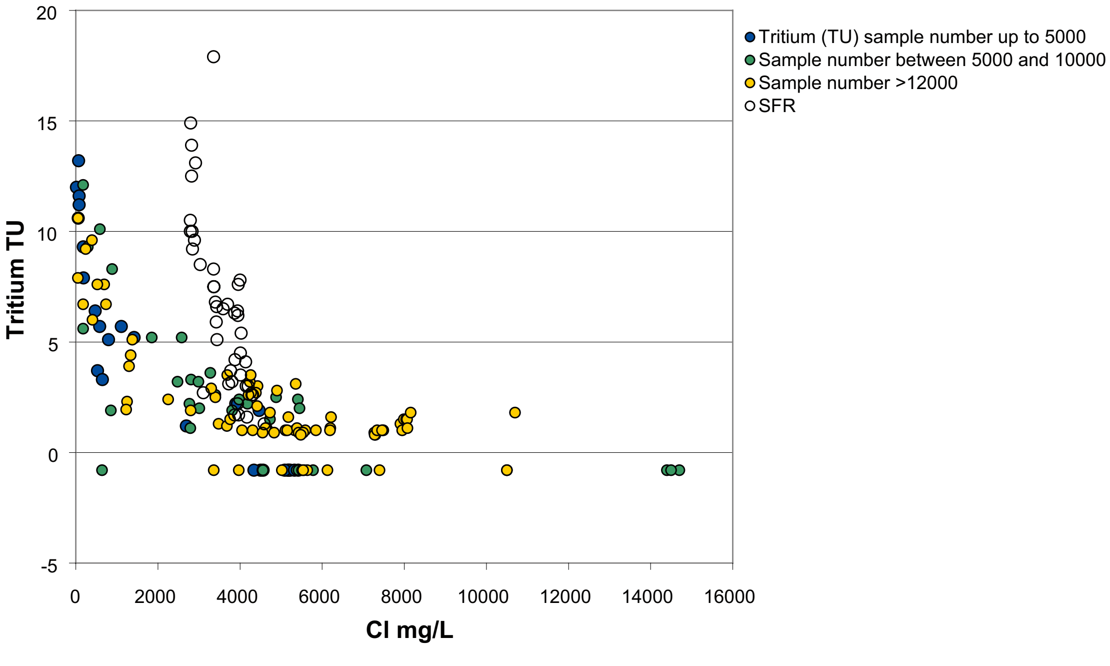


***Figure 4-14.** Tritium versus Cl plotted for groundwater samples from the last Forsmark update (20071130). Only samples with drilling contents less than 10% have been included. The samples have been divided based on their sample number in an attempt to reveal a possible evolution over time. The highest numbers (> 10,000) are the most recent samples whereas sample numbers < 5,000 represents results from the first years of the site investigation.*

With respect to tritium contamination by modern Baltic Sea and/or modern meteoric water entering into the bedrock during increased inflow, a successive change should be expected in the most sensitive part of the groundwater system, i.e. in the percussion boreholes located close to the surface. Figure 4-15 shows a plot of groundwaters from percussion boreholes and SFR boreholes only. It is obvious that the SFR samples mainly constitute mixtures of modern Baltic Sea

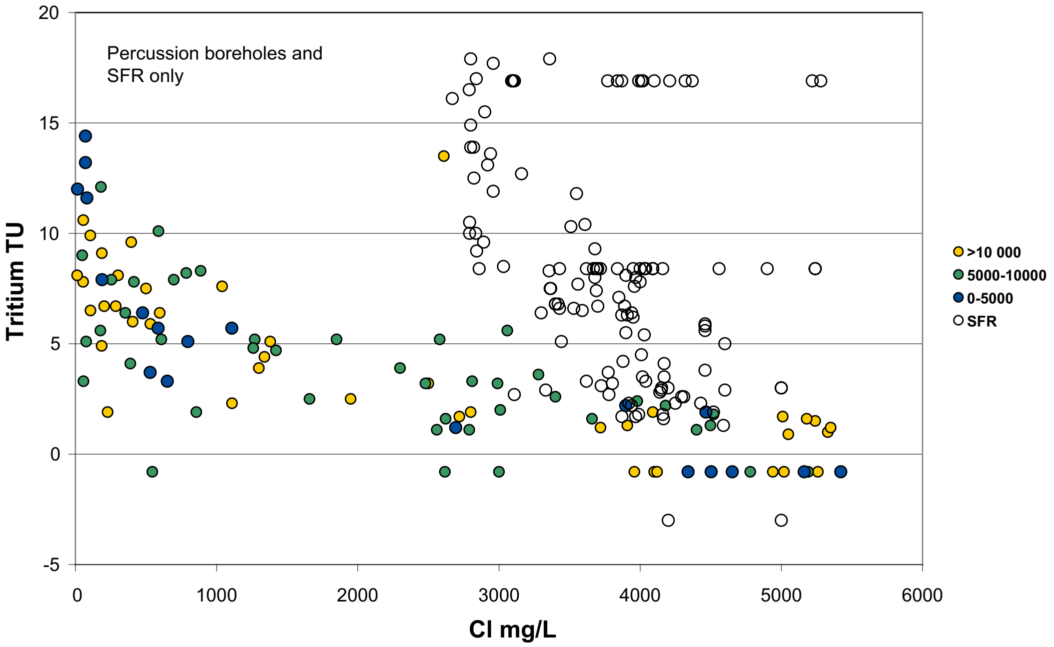


***Figure 4-15.** Groundwaters from percussion boreholes have been plotted versus Cl content. The samples have been divided based on their sample number in an attempt to reveal a possible evolution over time. The highest numbers (> 10,000) are the most recent samples whereas sample numbers < 5,000 represents results from the first years of the site investigation) (source F2.2-2.3 data set). Included for comparison are the SFR data.*

and Littorina seawater (with a possible addition of tritium from the SFR facility). The percussion boreholes, in contrast, show the highest tritium values in the very low saline waters (fresh waters). The only percussion borehole showing modern Baltic Sea water is HFM34 situated at drill site 11. However, boreholes sampled early during the site investigations (2002–2003) tend to have slightly lower tritium contents, thus supporting the idea of an increased draw-down of meteoric or modern Baltic Sea into the near-surface, gently dipping deformation zones which particularly characterise the hanging wall bedrock segment.

Examples from specific sections:

KFM08D: 669–676 m (elevation secmid –540 m). CCC sampling gave tritium contents between 0.8 and 1.0 TU. No correlation with drilling fluid. No indication of contamination due to modern meteoric or Baltic Sea water intrusions.

KFM08D: 828–832 m (elevation sec mid –664 m). CCC sampling gave 1.0–1.8 TU. No correlation with drilling fluid. No indication of contamination due to modern meteoric or Baltic sea water intrusions. Tendency towards higher tritium with higher salinity. Contamination during sampling is a possibility!

KFM06A: 341–362 m (elevation sec mid –298.54 m). The original samples close to this section length (354.00–361.13 m sampled in 2004 and 353.50–360.62 m in 2005) are below detection limit but the two later monitoring samples from 2006 give higher in tritium (1.1 TU) and show a small decrease with time in Mg and the other marine indicators (K, SO_4 and HCO_3). Cl content shows a small decrease from 4,650–4,620 mg/L.

KFM03A: 969–994 m (elevation sec mid –969.13 m). Monitoring section; first sampling in 2005 and 2006 showed below detection TU and the last one in 2007 gave detectable tritium (1.8 TU), but also a slightly more saline water to around 10,700 mg/L Cl compared to 10,500 mg/L Cl for the earlier samples.

NOTE: For these last two sections the original samples have tritium below detection limit so contamination by CCC equipment is less probable.

Conclusions

Several alternative explanations for the low but detectable tritium contents in the brackish and saline waters at Forsmark remain and possibilities include:

- Enhanced mixing of surface and especially modern Baltic Sea water through time partly caused by the extensive pumping related to performed dilution and tracer experiments, and long-term draw-down hydraulic pumping tests.
- Enhanced mixing of waters from SFR, which are enriched in tritium. These waters are mostly brackish marine waters of variable chloride contents.
- Contamination of tritium in the pumping equipment caused by high tritium in deionised water occasionally used during CCC sampling.

Less probable are:

- In situ production of tritium (probably too low production to give detectable contents)
- Analytical problems at the laboratory, i.e. exposure to tritium contamination.

4.3.9 Other issues

Data inconsistences

General plots based on all the data are systematically made to check for inconsistencies that may be related to sampling (e.g. on occasions tritium contamination) or analytical problems (e.g. on occasions bromide analyses). Such inconsistencies are checked and the data removed from the Sicada database if shown to be erroneous. Bromide data were plotted against chloride in Figure 4-16 to check for inconsistencies. Two normal trends are indicated, one a marine mixing line and the other a non-marine mixing line. Most data lie on or close to the mixing lines as expected, but some significant deviations are indicated on the plot, in particular for boreholes KFM07A (CCC sampling) and KFM03A (monitoring sampling), together with more expected mixing problems associated with the tube sampling exemplified by KLX08A. As plotted, this could be interpreted as a separate evolutionary trend for KFM07A and KFM03A compared to the other data, with far reaching repercussions in site understanding. However, these anomalous data were checked, found to be incorrect, and subsequently removed from the dataset. Figure 4-17 differentiates the Baltic Sea samples to illustrate the expected deviation (i.e. degree of mixing) in brackish groundwaters (4,000–6,000 mg/L Cl) between the two evolutionary mixing lines due to the Littorina influence.

Redox measurements

Downhole field values of Eh and pH presented in the Sicada dataset are not included in the above category descriptions since they are selected by reviewing the Chemmac logs and therefore are evaluated separately /cf. Appendix C in SKB 2007/. No field pH or Eh measurements have been carried out for the percussion boreholes. For cored boreholes field pH and Eh data are sporadic due to various reasons, for example, an absence of data may be a result of technical problems such as malfunctioning electrodes or data communication problems. However, the most common reason is that the electrodes do not measure stable or close enough values within the time available for the measurement. Another reason is that downhole equipment for hydrogeological tests has been used for pumping in several of the borehole sections and this does not allow Chemmac measurements.

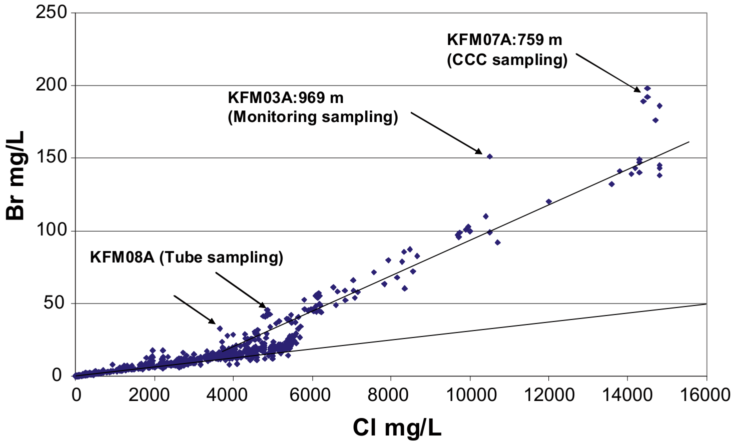


***Figure 4-16.** Chloride versus bromide for all Forsmark samples showing the anomalous data points.*

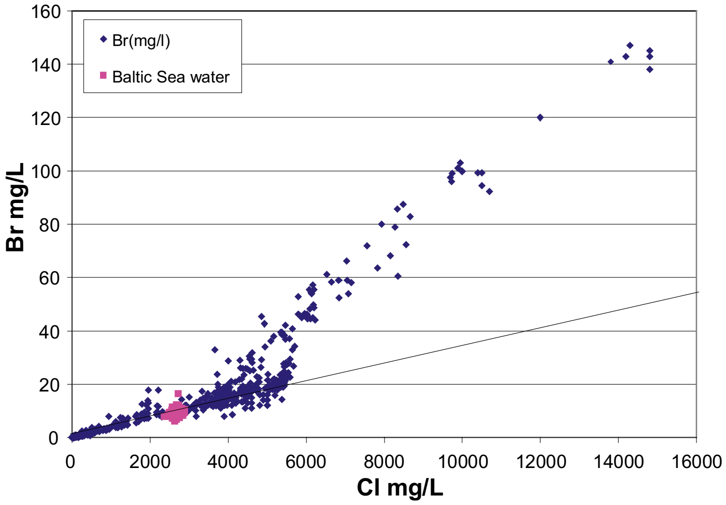


***Figure 4-17.** Chloride versus bromide for all Forsmark samples with the incorrect anomalous sample data removed. Marine trend line is indicated.*

Especially the Eh electrodes need time to stabilise and values from an initial measurement period (that varies in length) may not represent the Eh of the groundwater in the borehole section. Furthermore, pump stops or other disturbances that occur during a measurement period normally affect the Eh readings. All Chemmac values, therefore, have been selected from a point in the measurement sequence (generally at the end of the measurement period) when the different Eh and pH electrode-measured values are stable and in agreement. Suitable pH and Eh data for modelling purposes are indicated in the Sicada dataset in bold font. Note, however, that these chosen values do not always coincide with samples chosen as best representing the various groundwater categories. This is mainly due to the technical and sampling problems indicated above. In order to avoid this limitation, the same selected Chemmac values (T, O_2, Cond. Eh and pH) have been added to all the samples corresponding to the same section /Appendix C in SKB 2007/.

5 Hydrogeochemical evaluation

5.1 Presentation of data

Although this evaluation is restricted to the bedrock hydrogeochemistry, there is a necessary overlap with the SurfaceNet programme in order to quantify the input groundwater chemistry to the bedrock from the biosphere, i.e. the groundwater chemistry that actually constitutes the present-day Altered Meteoric end member. This has important repercussions on subsequent interpretations, particularly with respect to the range of recharge $\delta^{18}O$ and tritium values.

The hydrochemical data used in the evaluation are based mainly on Categories 1–4. Category 5, however, has not been ignored, for example, as mentioned in section 4.1.4 tube samples from the uppermost and lowermost parts of the borehole may provide major ion and $\delta^{18}O$ data of reasonably good quality that can be qualitatively used. In these circumstances care has been taken to specify why and how such data have been used.

In this section specific topics or issues have been addressed rather than a systematic evaluation of data producing a series of ion-ion cross plots which are largely presented in earlier reports /SKB 2005, 2007/ and also /Gimeno et al. 2008/. Topics/issues addressed are: a) trace element trends, b) uranium variability, c) radium and radon, d) sulphide variability, e) permafrost, f) origin and evolution of brackish marine (Littorina) groundwaters, g) origin and evolution of deeper saline groundwaters, and h) groundwater residence time.

Particular emphasis has been put on providing quality assured data and synthesising this data to provide an accurate description of site development from palaeohydrogechemical evidence and to produce a site visualisation that is realistic, informative and easily understood.

Depth plots are related to elevation, i.e. in metres RHB 70.

5.2 Trace and rare-earth elements

Trace elements and rare-earth (REE) components generally occur in groundwaters at concentrations of less than 1 mg/L /Drever 1997/. The following have been analysed within the Forsmark site characterisation programme and include Al, B, Ba, U, Th, Fe, Mn, Li, Sr, Sc, Rb, Y, Zr, In, Sb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu. Also included are commonly occurring metals such as Cu, Ni, Cr, Zn, Pb and Mo even though these may be influenced by contamination related to borehole activities discussed below. The risk of contamination is large also for aluminium (colloids may also be a problem), but this is still reported due to its importance for the modelling work; analytical results are, however, very uncertain and their usefulness can be questioned.

From the total trace element inventory, specific groups have been addressed separately depending on their use in understanding particular aspects of groundwater origin and behaviour. Some of the trace elements are addressed in detail in later chapters and therefore are only mentioned or excluded from this section, for example redox issues (Fe, Mn, S and Ce), origin of deep saline groundwaters (Ba, Sr, Rb, Li and B), and U and S^{2-} behaviour.

To establish accurately the groundwater distribution of certain trace elements of interest to repository performance assessment (e.g. Mo, Ni, Zn, Ba, Sr and REEs) and the mineralogy of the water-conducting fractures sampled, provides the opportunity to calculate their solubility limits and test models of speciation and transport.

5.2.1 Quality of data

The groundwater quality evaluation and categorisation presented in Chapter 3 was not extended to the trace element data, only with respect to whether the trace element data suite was reasonably complete, partially complete or lacking. This was mainly due to the fact that many of the trace element data are sensitive to: a) palaeo-events resulting in the introduction and mixing of different groundwater types, b) sources of potential contamination related to borehole activities, c) sampling when different pump rates and time periods are used, and d) analytical uncertainty when there is close to detection amounts of dissolved elements in the samples collected. The probability of one or more of these possibilities occurring, underlines the difficulty of knowing the trace element composition to be expected in a representative groundwater sample.

Potential contamination problems resulting from hydraulic testing of groundwater flow conditions in some monitoring borehole sections have been discussed in section 4.3.5. In addition, general contamination from drilling and the raising and lowering of downhole equipment in many boreholes may be problem and has to be considered. Moreover, there is some evidence of significant variation in trace elements during the sampling period (cf. section 4.3.6), especially from some of the low transmissive single fractures sampled in the footwall bedrock segment (i.e. borehole KFM01D in fracture domain FFM01). Finally, the introduction of Littorina Sea water into the bedrock system is characterised by a trace element chemistry which can differ from both earlier and later groundwater types.

As a result, many of these data have to be assessed on an element to element basis in order to assess systematic depth trends and/or the conservative behaviour of compatible element pairs.

All plots are based on Category 1–4 samples unless otherwise stated; samples when unsuitable (i.e. anomalous) are indicated on the plots.

5.2.2 Trace elements and depth trends

In general, different trends in trace element concentration may be expected in normal groundwater systems, for example: a) some trace element concentrations, irrespective of their source, will be expected to decrease as they are transported through the bedrock groundwater system with increasing depth; adsorption by manganese and iron oxides is one of the main uptake processes, and b) other trace elements will increase with depth due to their release from water/rock interactions involving the solubility of phases containing the elements as major constituents (e.g. oxide/hydroxide, carbonate or sulphide); these phases will provide an upper limit to the element's concentration. At Forsmark, however, this simplistic pattern is complicated by the periodic introduction of widely differing groundwater compositions, particularly since the last deglaciation.

Problem of contamination

Figure 5-1 showing the distribution of all available copper data with elevation exemplifies the characteristics of several of the trace elements. The figure shows a narrow range of Cu values (0–1 ug/L) at shallow depth (0–200 m), which changes to approximately 0–4 ug/L at 200–650 m depth; there is no obvious depth trend within this latter interval and only sparse data from depths greater than 650 m. On closer inspection, some data represent time-series variations for four sampled sections in three boreholes which have sufficient measurements. Of these three boreholes, KFM01D and KFM08A represent sampling from low transmissive fracture zones in the footwall bedrock segment (i.e. Fracture Domain FFM01) using the newly developed SLT (Sampling equipment for Low Transmissive fractures) technique /Nilsson et al. 2006/. Borehole KFM09A is located at the margin of the candidate site to the north-west close to the Eckarfjärden DZ and sampled by standard CCC procedures. All represent brackish non-marine groundwaters and high copper concentrations characterise the initial samples collected during the sampling period. Over time periods ranging approximately from 2–7 weeks these values decrease to similar levels shown by the brackish marine Littorina-type groundwaters.

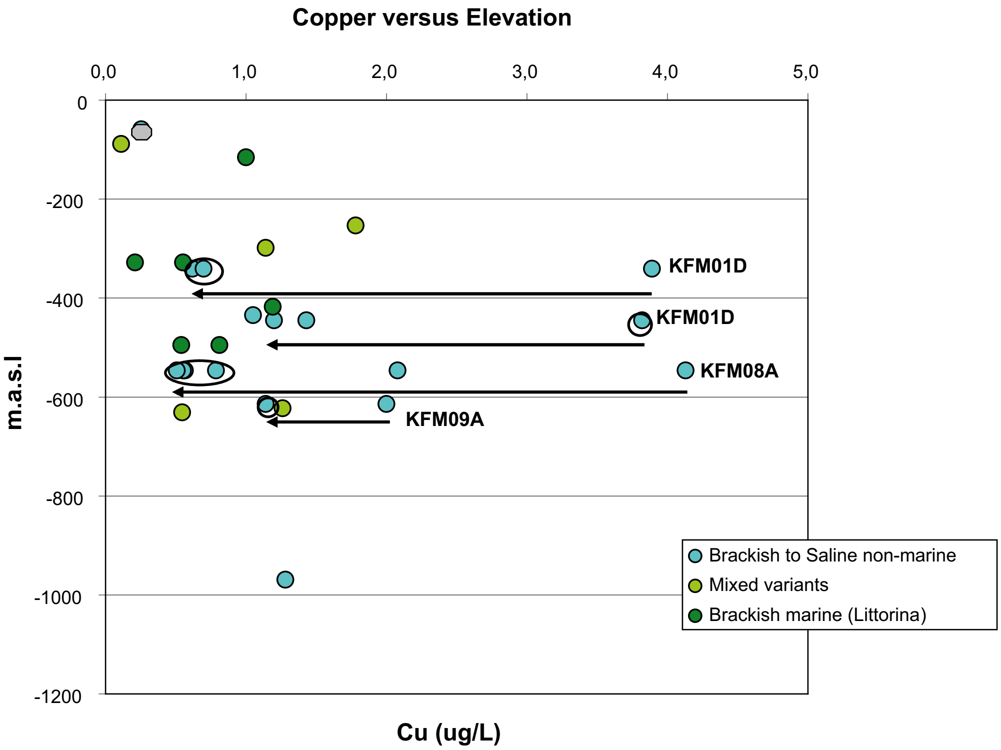


Figure 5-1. *All available Cu data versus elevation. The data are subdivided into the different groundwater types and also show time-series variation during sampling from three boreholes. Arrows show a decrease in Cu with time and the ringed samples the content associated with the samples selected as being of 'good quality' based on major ions and environmental isotopes etc. Grey infilled circle is fresh non-marine groundwater.*

It is also worth noting that of the four sections in question, the final sample in the time-series accepted as representing 'good quality' conforms to three out of the four sections. Only one of the KFM01D sections at elevation –445.17 m records a copper content which is too high. This also underlines the point that quality control of these trace element data should be assessed on an element to element basis.

Considering the lower copper values as more representative, Figure 5-2 (based on Categories 1–4) still shows no obvious depth trend unless only the brackish to saline non-marine groundwaters are considered. A weak increase with depth is suggested but not convincing; additional data from depths greater than 650 m are required. A similar pattern is also characteristic for As, Cr, Co Zn, Mo, Zr and Ni although not always is there a systematic decrease in concentration during the time-series measurements; increases or general fluctuations also have been recorded (e.g. Figure 5-3).

The observed fluctuations for many trace elements during sampling may be due to incoming residual sources of contamination (e.g. from drilling activities) or due to perturbation of the natural groundwater system during pumping, or a combination of both. Sources of residual metal contamination may have resulted from borehole activities including: a) constant wear on the drilling crown and drilling rods, b) raising and lowering cables and probes used in borehole logging, and c) during operation of the sampling equipment. As discussed in section 4.2.2, because of high drilling head water pressures and the hydraulic nature of individual boreholes, contamination may be expected along most open fractures. Contamination would tend to enter rapidly, but also be flushed out more rapidly in higher transmissive fracture zones (e.g. the gently dipping deformation zones associated with the hanging wall bedrock segment) than in single fracture systems of low transmissivity (e.g. more typically associated with the footwall bedrock segment (i.e. fracture domain FFM01). This is reflected in Figures 5-1 and 5-3 where residual high values are often associated with deep, brackish to saline non-marine groundwaters sampled in low transmissive zones intersected by, for example, boreholes KFM01D and KFM08A, when compared to brackish marine (Littorina) type groundwater normally associated with more highly transmissive fracture zones. These figures also indicate that with sufficient pumping most of these contamination effects can be removed.

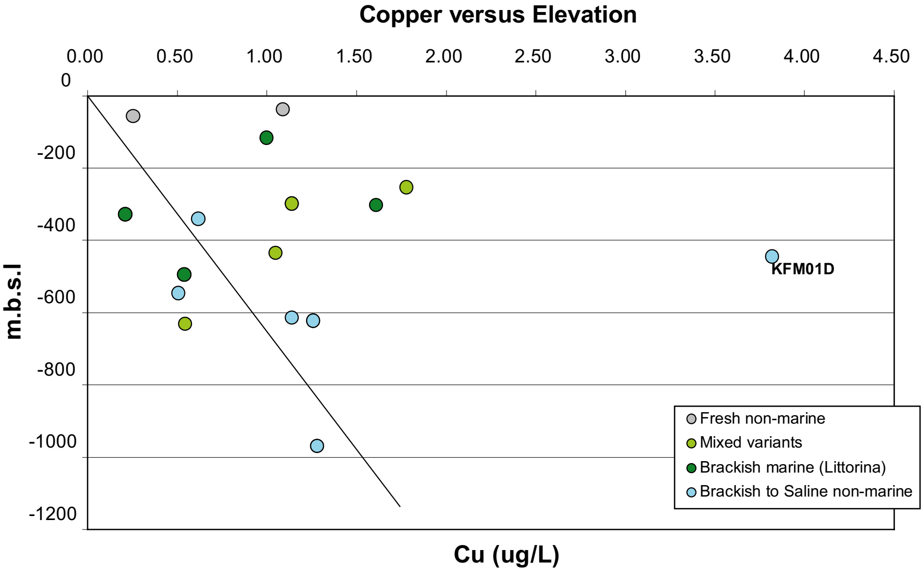


Figure 5-2. Cu plotted against elevation for Category 1–4 data. A weak increase with depth is suggested if the brackish to saline non-marine samples are considered. (Updated data included).

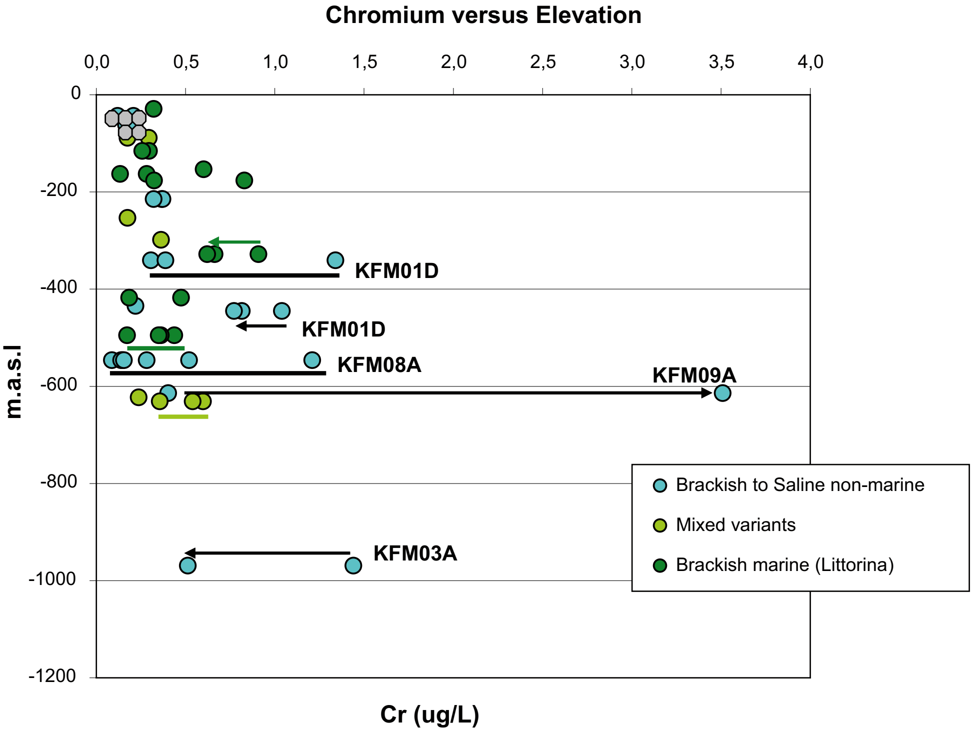


Figure 5-3. All available Cr data showing time-series variation during sampling of four boreholes. Arrows show direction of increase or decrease of Cr during the time series; horizontal lines indicate variability. Grey infilled circles represent fresh non-marine groundwater. (Updated extended 2.3 data included).

Other trace elements show small enrichments associated with some of the mixed group of groundwaters, in these cases mostly groundwaters representing a weak Littorina signature associated with brackish non-marine groundwaters, for example Mo and As in Figures 5-4 and 5-5. However, these higher values are also associated with monitoring borehole sections, an observation that may be coincidental, but is more likely to be an indication of trace element mobility caused by high pump rates when preparing the borehole sections for periodic monitoring.

In summary, the behaviour of certain trace metals (e.g. Mo, As, Cr, Co, Cu, Pb and Ni) is difficult to evaluate in the Forsmark groundwaters because of:

- Incursion and mixing of different groundwater types at different stages in the past, particularly since the last deglaciation.
- Contamination resulting from borehole activities which may have affected mainly low transmissive fractures characteristic of fracture domain FFM01 in the footwall bedrock segment. Subsequent pumping when sampling may have served to mobilise many of these residual elements resulting in enhanced values. This further underlines the importance of adequate pumping prior to sampling to help remove excess trace metal contamination.
- Periodic monitoring of borehole sections where high pump rates are used to prepare the section for sampling, i.e. by removing three section volumes of water followed by immediate sampling. This activity may also have served to mobilise many of these elements, both residual types from drilling activities and those naturally occurring elements from mixed sources loosely bound along the fracture systems.
- In some cases a groundwater sample characterised as being of good quality, based on major ions and isotopes etc (i.e. Categories 1–3), was sampled when the trace element contents had stabilised. There are other cases, however, when the chosen groundwater sample had not achieved trace element stability, therefore suggesting contamination.
- The relationship of some metals with uranium was tested to shed some light on the possible origin of the elevated uranium in some of the Forsmark groundwaters (cf. section 5.3). Uranium is naturally often found in association with As, Mo, V (or PO_4); however no obvious correlation was found.

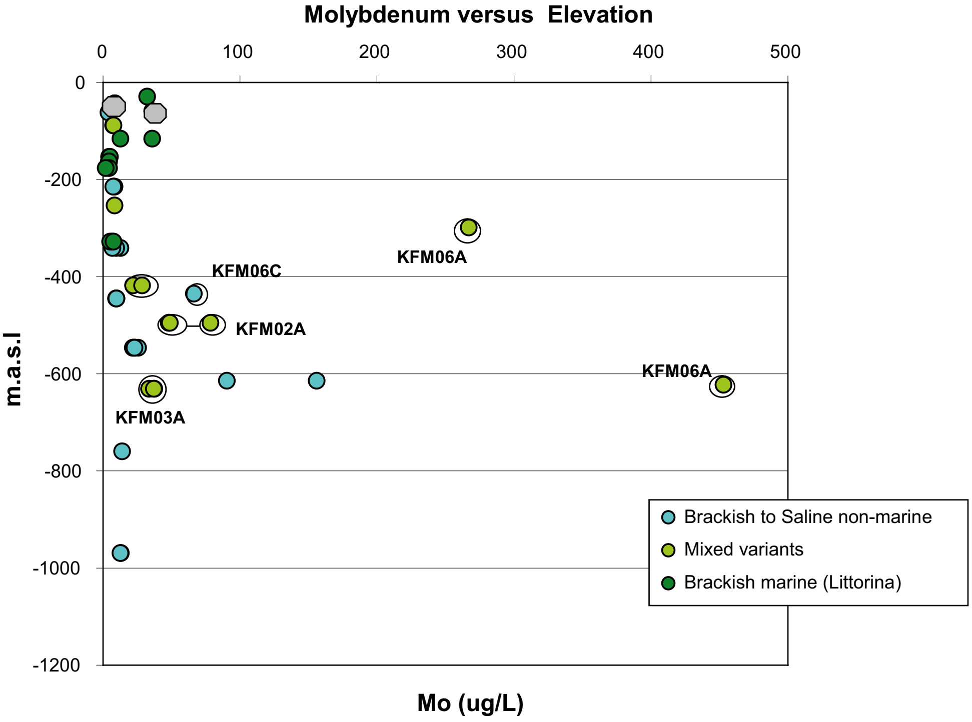


Figure 5-4. *All available Mo data subdivided into different groundwater types; ringed samples represent monitoring borehole sections. Grey infilled circles represent fresh non-marine groundwater. (Updated extended 2.3 data included).*

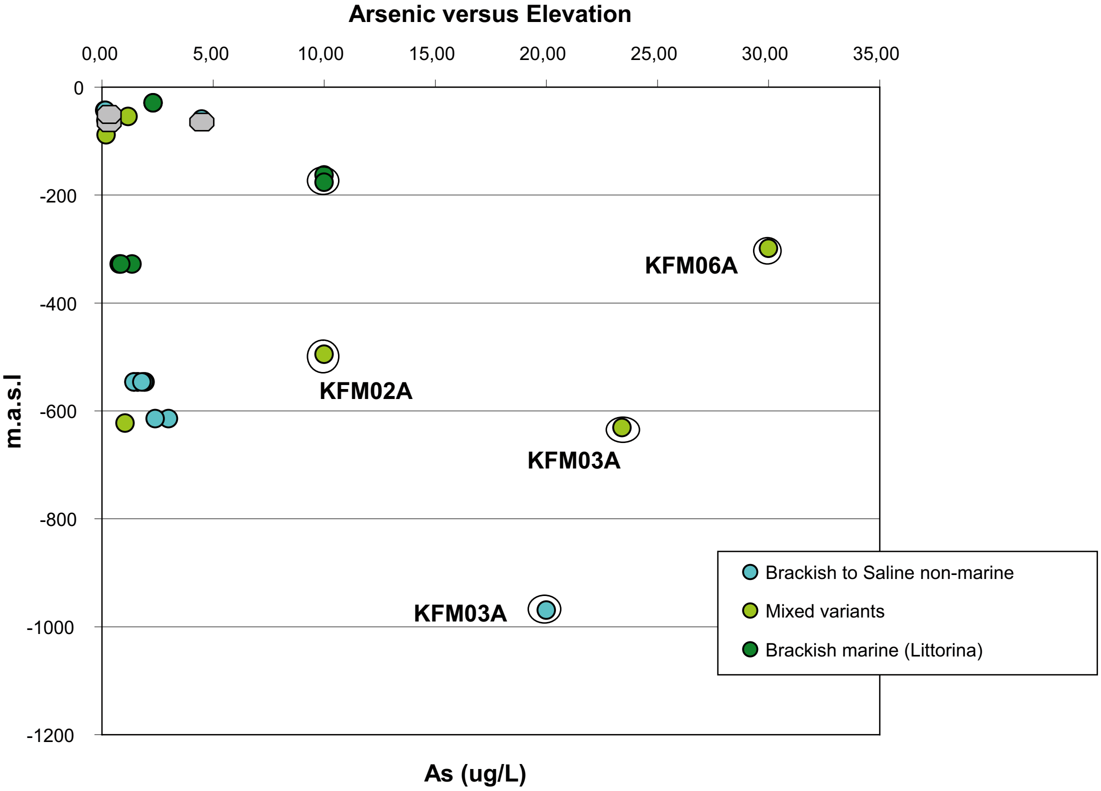


***Figure 5-5.** All available As data subdivided into different groundwater types; ringed samples represent monitoring borehole section. Grey infilled circles represent fresh non-marine groundwater. (Updated extended 2.3 data included).*

5.2.3 Rare-earth elements (REEs)

Rare earth elements (REEs) are usually evaluated collectively due to their similar chemical behaviour. Normally REEs exist as trivalent species, but Ce may be oxidised to Ce(IV) while Eu in contrast may be reduced to Eu(II).

The REE contents in the Forsmark groundwaters are generally low with below detection levels in the deeper groundwaters characterised by saline non-marine groundwaters. From ten core borehole sections, however, representing depths from 100–500 m, it was possible to analyse the REEs; for the chondrite normalised curves see Figure 5-6. Eight of the analysed samples consisted of brackish marine waters, one has a close to fresh water composition (Cl = 640 mg/L, KFM02A:108 m) and one was classified as brackish non-marine (KFM10A:215 m). Interestingly, the latter showed the lowest REE contents and only La and Ce were above detection limit. The other samples showed largely similar uniform REE patterns with a slight increase in HREEs. This is normally interpreted as typical for dominantly carbonate complexation. Sample KFM01D: 253 m elevation deviates from the rest of the samples in having a positive Eu-anomaly. The representativity of the REE analyses seems to be good (apart for Eu for which there was only one collected sample to date) judged from repeated analyses of time series samples.

Samples from percussion boreholes where plotted separately but show similar REE patterns (and also REEs contents) as the groundwater from the cored boreholes (Figure 5-7). Both Fresh (HFM04 and HFM16) and brackish marine waters (most typically HFM13 and HFM19) where represented. All of the samples, irrespective of chloride contents, have bicarbonate contents above 120 mg/L.

A more comprehensive study of the REE fractionation in this system is needed in order to understand the complete behaviour of these elements, their involvement in reaction and mixing processes and their potential use as geochemical indicators. This work will need the study of the REE contents and distribution in the different sources and sinks present in the system, that is, the rock and the fracture fillings, together with an improvement of the detection limits in waters.

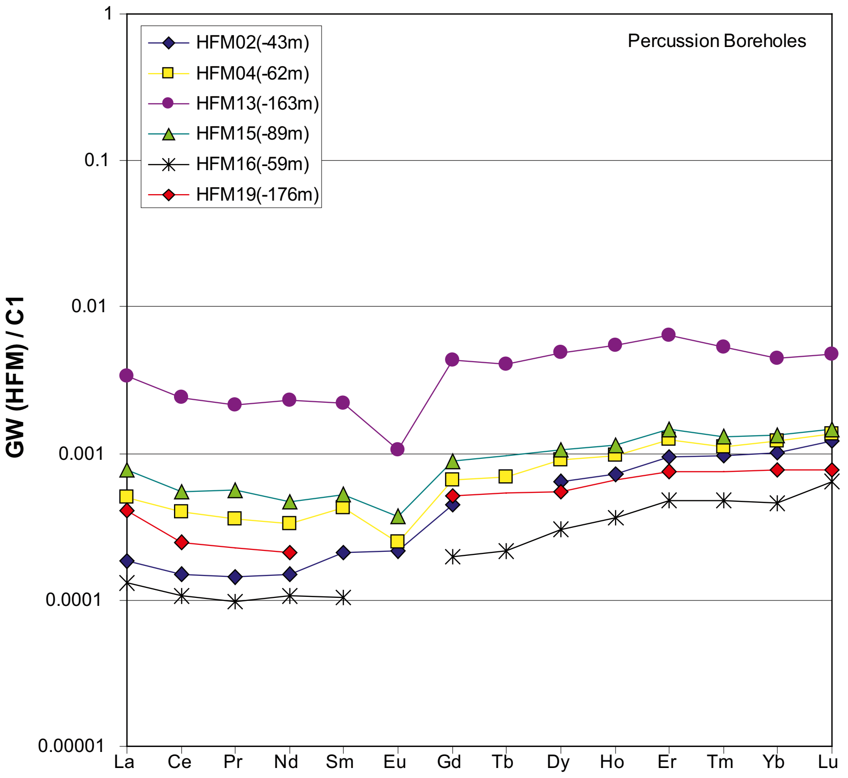


***Figure 5-6.** Chondrite normalised groundwater REE curves from percussion boreholes.*

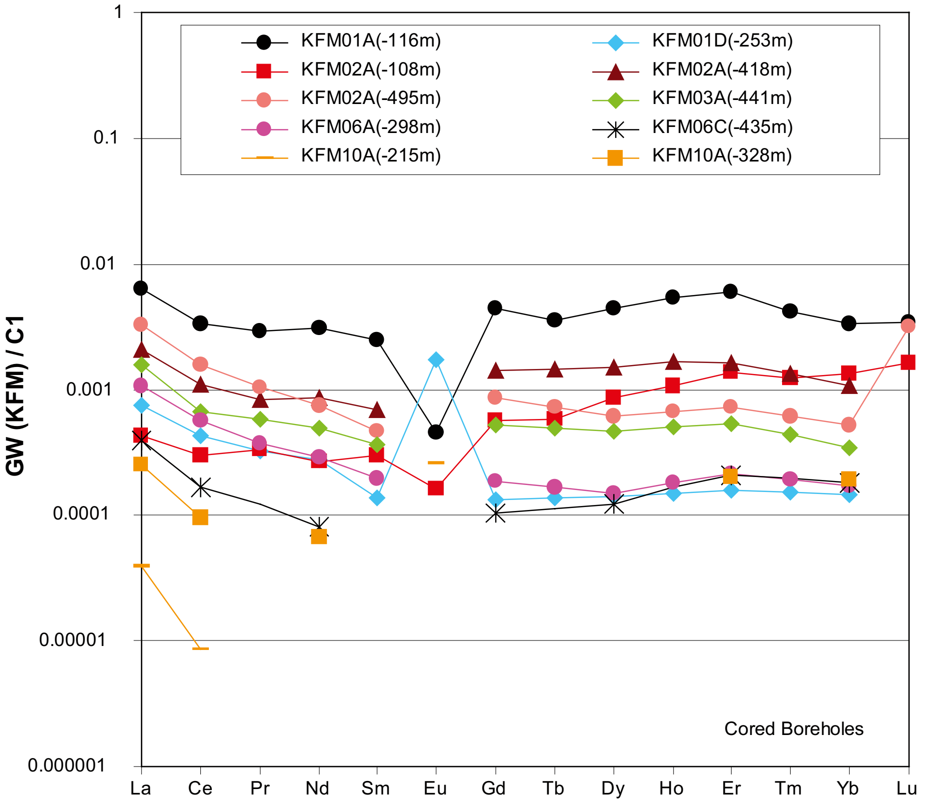


***Figure 5-7.** Chondrite normalised groundwater REE curves from cored boreholes.*

5.3 Uranium and its variability in groundwaters and bedrock

5.3.1 Background

The distribution of uranium in the Forsmark groundwaters has been the focus of discussion and conjecture since the initial observation of elevated uranium concentration corresponding to a narrow range of chlorinity coinciding mostly, but not always, with the brackish marine (Littorina Sea) groundwaters (Figure 5-8). As an integral part of the hydrogeochemical studies, but also from a safety assessment viewpoint, the importance of explaining these elevated uranium concentrations therefore became prioritised. Needless to say several differing hypotheses have emerged which have been individually addressed.

Like many other groundwater trace element constituents, but more so for uranium, sampling under controlled conditions is of paramount importance, for example, the initial removing of contamination from pre-sampling borehole activities, sampling using optimum pump flow rates (e.g. minimising changes in groundwater chemistry and redox conditions), adequate period of pre-sampling monitoring to ensure stabilisation etc. Care is also required when sampling from low transmissive fractures to avoid removing loosely bound trace constituents from the fracture surfaces. There are numerous examples were trace elements in the groundwater finally selected for analysis are anomalously high, even though the major constituents indicate stability (cf. section 5.2.3). The uranium data have been carefully scrutinised to evaluate such possible negative effects and, while anthropogenic effects undoubtedly have influenced many of the uranium contents to a degree, the overall elevation of uranium in the measured groundwaters is a hydrochemical anomaly in the Forsmark bedrock that needs to be explained.

Given that there may be uncertainty with respect to the quality of some of the groundwater samples analysed, fracture coating material, if possible selected from the same open fracture sampled for groundwater, has been analysed for the uranium decay series isotopes together with the groundwater suite of samples. Can the fracture coatings help explain the observed anomaly?

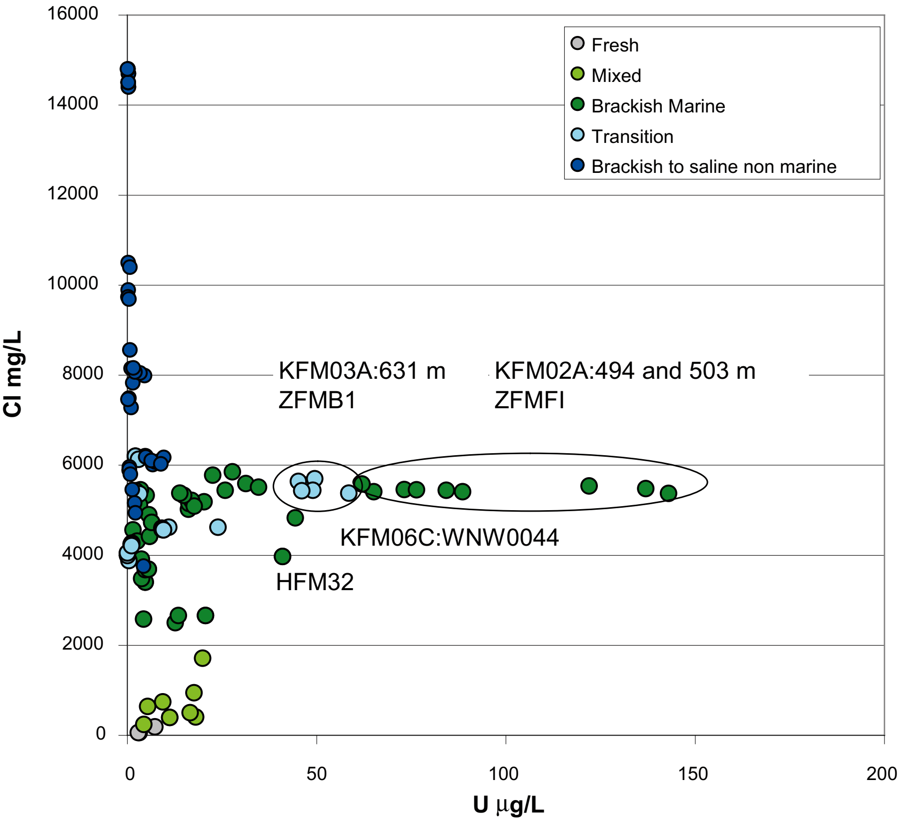


Figure 5-8. Cl versus U for groundwaters from Forsmark. A large number of data are plotted for KFM02A around 500 m depth representing groundwaters from the gently dipping deformation zone ZFMF1.

5.3.2 Distribution of uranium in the bedrock and possible sources

From bulk fracture coating analyses it is obvious that enhanced uranium concentrations occur in some of the fracture systems within the Forsmark candidate site /Gimeno et al. 2008/. Most of the samples analysed had uranium contcentrations in the range 0.1 to 164 ppm, except in two samples from KFM03A:643.80–644.12 m and KFM03A:644.17 m, which have contents of 2,200 and 2,310 ppm U respectively. Out of the 70 fracture samples analysed, nine show uranium concentrations higher than 24 ppm in combination with a U/Th ratio greater than 10, which strongly indicates deposition of the uranium in the fractures. Of these nine samples taken from depths ranging from 133–633 m, seven belong to the gently dipping deformation zones which characterise the hanging wall bedrock (i.e. fracture domain FFM03), and one is sampled from KFM11A, to the west of the large NW-trending Singö deformation zone. It has only been possible to identify one uranium-bearing phase and that is from sample KFM03A:644.17 m; this comprised one small grain of pitchblende from the fracture coating material which also recorded the highest uranium concentration (Figure 5-9). Although not demonstrated, part of the uranium is assumed to be sorbed onto clay minerals or Fe-oxides in the fracture coatings.

The bedrock within the candidate site is generally low in uranium (< 10 ppm) but, some of the pegmatites show slightly enriched uranium values; a maximum value of 62 ppm is indicated by gamma spectrometric data /Stephens et al. 2007/. However, uranium mineralisations are not unknown in the region (Figure 5-10) and several are found associated with iron ores in the northern Uppland area /Welin 1964/. Three types of mineralisation have been identified: 1) The oldest type (ca 1,785 Ma) is related to the Late Svecokarelian epoch consisting of disseminated uraninite precipitated from oxidation-reduction reactions in the iron-bearing skarn ores. 2) The second type of mineralisation (ca 1,585 Ma) occurs in the fissured bedrock, resulting in the formation of pitchblende, haematite and some sulphides related to mineralised fractures or veins of chlorite, calcite and quartz. 3) A younger, less well-constrained period of uranium mineralisation was distinguished, consisting of pitchblende precipitation in a chemically reactive 'ferriferous rock' /Welin 1964/.

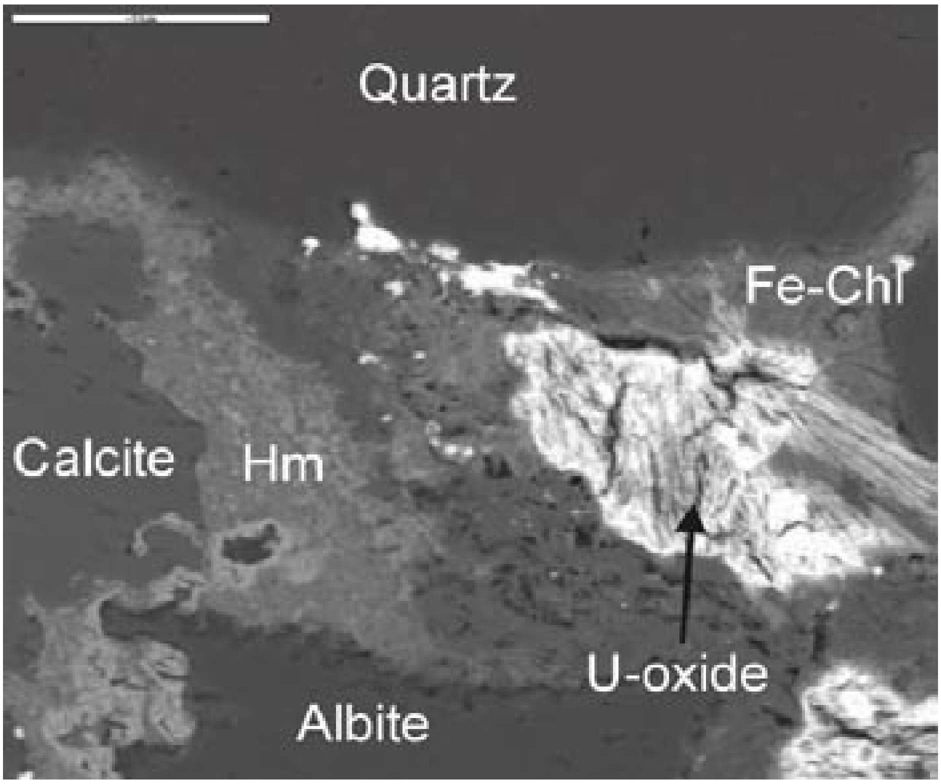


Figure 5-9. *Altered U-oxide (pitchblende) with chlorite (Fe-Chl), haematite (Hm), calcite (KFM03A:644.1m). Back scattered electron image; scale bar 50 µm.*

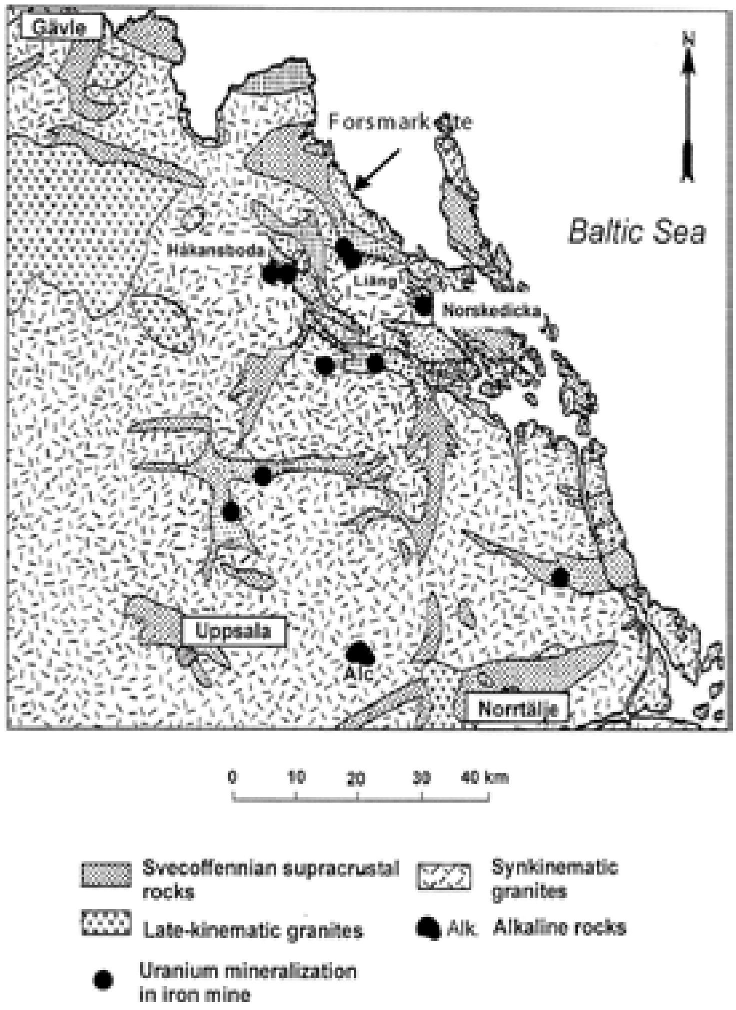


Figure 5-10. *Localised uranium mineralisations in northern Uppland, near Forsmark /Welin 1964/.*

Asphaltite (cf. section 2.2.1) has been identified in fractures in the upper 150 m in Forsmark and based on analyses of stable carbon isotopes and biomarkers, the asphaltite found in fractures in the crystalline basement at Forsmark has been shown to be of biogenic origin /Sandström et al. 2006a/. The most plausible source rock is the late Cambrian to lower Ordovician Alum Shale that covered most of southern Sweden during the Palaeozoic. Alum shales may be enriched in uranium and some of the asphaltite occurrences in south central Sweden are high in uranium and thorium (i.e. termed thucholite: An acronym for Thorium, Uranium, Carbon and Hydrogen (TH, U, C, H)) /Welin 1966/. However, the fracture asphaltites analysed from the Forsmark site show low uranium and thorium and probably do not contribute significantly to the elevated uranium contents in the groundwaters.

Based on the information above, fracture coatings with large variations in uranium content occur in the fractures at Forsmark and that in these fracture coatings, both U(IV) and U(VI) may be hosted in different phases and some may also be sorbed onto mineral phases such as haematite and clay minerals.

5.3.3 Distribution of uranium in groundwaters

From analyses of groundwaters sampled in the cored boreholes at Forsmark it is indicated that part of the uranium found in the fractures is easily mobilised during certain conditions, especially with respect to redox conditions and bicarbonate content /SKB 2005, Appendix C in SKB 2007/. This is suggested in Figure 5-11 which shows a correlation between fracture fillings with a high uranium content and groundwater samples taken from the same depths.

Elevated uranium contents (up to ~150 µg/L) have been detected in some of the brackish marine groundwaters (compare with about 3 µg/L uranium concentration in seawater) from depths of 50–650 m (Figure 5-12). The two sections showing the highest values belong to the gently dipping deformation zones ZFMF1 at 497 m in borehole KFM02A and ZFMB1 in borehole KFM03A at 633m. The brackish to saline non-marine groundwaters show generally low uranium contents (usually < 2 µg/L) despite depth; only one section in KFM08A shows increased values (4–10 µg/L U).

Large variations in uranium are measured in surface and near surface waters (from 0.05 to 40 µg/L; not shown in Figure 5-12). This is common and usually ascribed to variations in redox and in concentrations of complexing agents, notably bicarbonate, the presence of which enhances solubility and hence mobility of uranium. Explaining the large variations in uranium at intermediate depths (Figure 5-12), in contrast, is more complex as several different explanations are possible.

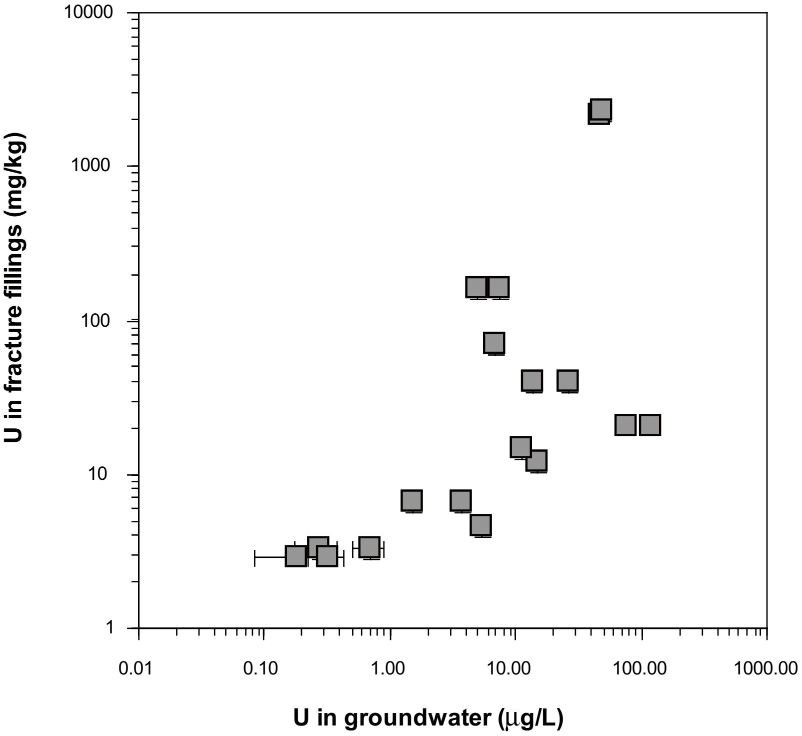


Figure 5-11. *Uranium content in fracture fillings (ppm) versus uranium in groundwater samples (µg/L). The fracture filling samples are from the corresponding drill core length. The precision of both water and fracture analyses is ~15% /Sandström et al. 2008/.*

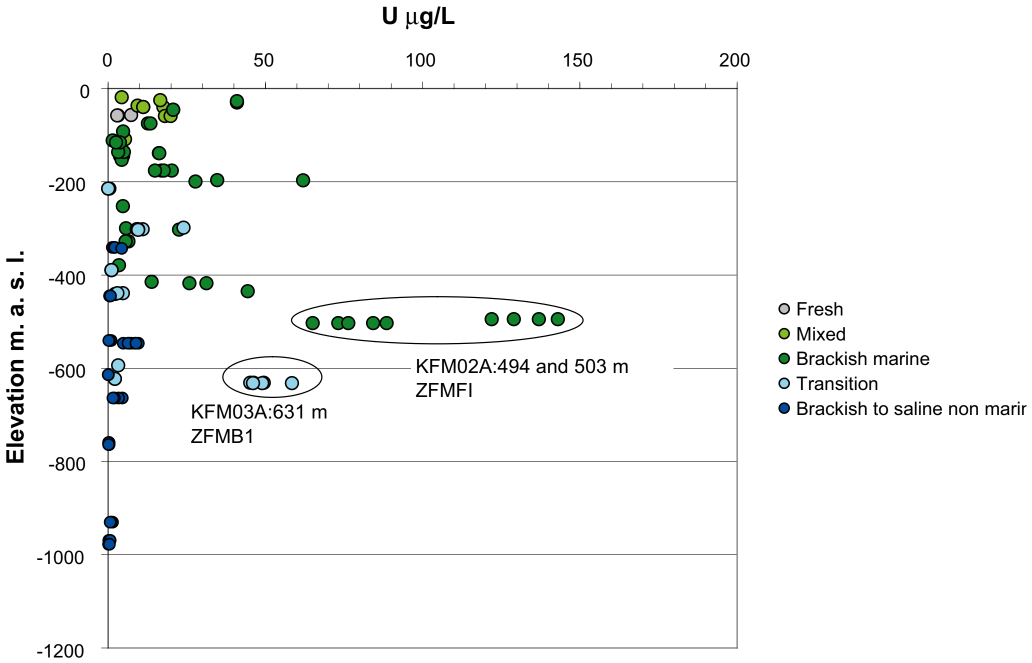


***Figure 5-12.** Uranium in groundwaters from percussion and cored boreholes versus elevation. Only representative samples are included and ringed samples denote time series measurements for KFM03A: 631 m (Categories 1–3; cf. section 3.1.2).*

The reasons for the elevated uranium contents in the brackish marine groundwaters at intermediate depth has been discussed in, for example /Appendix A and C in SKB 2007/ where it was concluded that:

- Fracture fillings with high uranium contents correlate with groundwater samples taken from the same depths (Figure 5-10) and it is concluded that the elevated uranium contents in the groundwater is related to mobilisation of uranium from the fracture mineral/rock system.
- Despite negative Eh-values, elevated uranium contents in the groundwaters are restricted to samples showing mildly reducing conditions (Eh between –140 to –200 mV) whereas the more reducing groundwaters are low in uranium /SKB 2007, Appendix C/. It was also concluded that these mildly reducing conditions allow for uranium-carbonate complexation (uranium-carbonate complexes are stable when pH>8, which is mostly the case).
- A study of uranium oxidation states in groundwater by /Suksi and Salminen 2007/ from the section showing the highest uranium content (~120 µg/L), showed a total dominance of U(VI) in the groundwater.
- Even though elevated uranium contents seem to be related to present fresh meteoric water, and brackish marine groundwaters introduced after the last deglaciation, it seems unlikely that uranium has been mobilised and transported into the bedrock by these groundwaters, based on the wide range in uranium contents and the spatial distribution of elevated uranium groundwaters.
- Disturbances caused by the drilling may have enhanced the mobility of the uranium, especially in fractures potentially opened for groundwater flow by the drilling.
- Microbial activity (possibly enhanced by perturbation in connection with the drilling) may have increased the uranium mobility /Appendix B in SKB, 2007/.
- Colloid uptake plays a minor role in the mobilisation and transport of the uranium /Nilsson et al. 2006, Bergelin et al. 2008, Appendix B in SKB 2007/.

- Changes in redox conditions associated with the close proximity of the high voltage cable passing through the candidate area may possibly have had local effects on the uranium mobility /Appendix F in SKB 2007/.

Additional Forsmark 2.2/2.3 data comprising uranium contents from sections selected for groundwater monitoring indicate that most of the sections originally showing low uranium remain low and sections with high uranium remain high (and in several cases even higher during the monitoring phase as discussed in the introduction). Recent speciation-solubility calculations indicate possible equilibrium with amorphous uranium phases such as $UO_{2.66}$, $UO_{2\,(am)}$ and $USiO_{4\,(am)}$ for groundwaters with the highest uranium contents /Gimeno et al. 2008/. The best fit was found for $UO_{2.66}$ (whereas oversaturation was indicated in respect of $UO_{2\,(am)}$ and $USiO_{4\,(am)}$) but the calculations was uncertain due to lack of corresponding measurements of Eh, pH and U(IV)/U(VI) (measurements of sample from the same section at the same time).

Not only dissolution of uranium phases but also sorption/desorption of uranium need to be considered when discussing uranium mobility. Sorption coefficients (K_d) for U(VI) measured on fracture fillings from deformation zone ZFMA2 at around 50 m depth (KFM01B) show values of around 2×10^{-2} (m^3/kg) /Byegård et al. 2008/.

5.3.4 Uranium decay series measurements

Uranium decay series measurements on groundwaters

Analyses of isotopes in the uranium decay series can be used to infer groundwater redox conditions. Not only contemporary conditions can be characterised, but also evidence of past changes (e.g. during the last deglaciation some 10 ka ago) can be preserved in minerals which coat the fracture walls along groundwater pathways. Uranium decay series data for groundwaters and solid fracture phases from the Forsmark site have been analysed and are discussed below.

It is the first part of the uranium decay chain that is usually used for the USD series analyses and in this case mainly ^{234}U and ^{238}U for the water samples and ^{238}U-^{234}U-^{230}Th in the solid samples (fracture coatings).

Isotope	**^{238}U→**	^{234}Th→	^{234}Pa→	**^{234}U→**	**^{230}Th→**	^{226}Ra
Half-life	4.5×10^9y	24.1d	1.2min	2.5×10^5y	7.6×10^4y	1.6×10^6y

A summary of the contents of chloride, bicarbonate, uranium and measured $^{234}U/^{238}U$ activity ratios for the different groundwater types are shown in Table 5-1.

For groundwater samples the ^{238}U and ^{234}U activities (Figure 5-13) show that most of the waters with elevated uranium concentrations (higher than 5 µg/L ~ 60 mBq/kg) have $^{234}U/^{238}U$ activity ratios between 2 and 3. The samples from the hanging wall bedrock segment showing the highest uranium concentration are (KFM02A:497m; deformation zone ZFMF1) with a ratio around 2, and sample KFM03A:631m (deformation zone B1) with an activity ratio of around 1.5 (Figure 5-14).

Table 5-1. Cl, HCO_3, U and $^{234}U/^{238}U$ activity ratios (AR) for different groundwater types at Forsmark.

Water-type	Cl mg/L	HCO_3 mg/L	U µg/L	$^{234}U/^{238}U$ AR
Dominantly Fresh	0–2,000	317–450	2–20	2–3.1
Brackish Marine	2,000–6,000	45–260	1.5–143	2–4
Transition zone sample (Marine/Non-marine	5,500–6,000	23–34	45–59	1.5
Brackish/Saline non-marine	4,000–15,000	7–35	>0.1–2 One sample 6–8	2–3.6

There is no correlation between $^{234}U/^{238}U$ activity ratio and uranium content (Figure 5-14), or $^{234}U/^{238}U$ activity ratio and depth (Figure 5-15), which is quite expected considering that the samples represent fractures with different transmissivities and geological history. Both low (1.5) and relatively high (3.5–4) activity ratios occur from 150–700 m (Figure 5-15). A majority of samples show, however, activity ratios < 2.8. In reducing groundwater conditions from intermediate to great depth from, for example Olkiluoto and Äspö, activity ratios ≥ 3 are much more common and the uranium contents are usually lower /Pitkänen et al. 1999, Tullborg et al. 2003/. Ratios close to one in conjunction with high uranium concentrations can be interpreted as being indicative of oxidising.

From the measured uranium contents and $^{234}U/^{238}U$ activity ratios available in the extended 2.3 dataset for the different groundwater types, it can be concluded that:

- The highest uranium contents are associated with some of the brackish marine groundwaters and appear to have accumulated in the transition zone between brackish marine and brackish non-marine groundwaters (KFM03:631 m).
- The brackish marine groundwaters all have $^{234}U/^{238}U$ activity ratios much greater than that of seawater (1.158±0.008 at a salinity of 24‰ /Andersson et al.1995/).
- The samples showing the highest values (>45 µg/L) are from ~ 500 m depth in the gently dipping deformation zone ZFMF1 and ~ 630 m depth in Zone ZFMB1.
- There are several samples of brackish marine groundwater that show low uranium contents, so elevated uranium is not typical for this groundwater type.
- One of the brackish to saline non-marine groundwaters, representing a depth of ~ 550 m in a possible deformation zone, showed a small increase in uranium content to 4–10 µg/L.
- All of the $^{234}U/^{238}U$ activity ratios are significantly greater than unity which theoretically can indicate an absence of rapid oxidative dissolution of uranium (which in such cases would have resulted in activity ratios close to one).
- However, in a heterogeneous and complex system as Forsmark, this may not be so clear cut as it is not possible to exclude the dissolution and contribution from a partly oxidised uraninum mineral phase that could lower the activity ratios because of equal dissolution rates for both isotopes in the oxidised state.

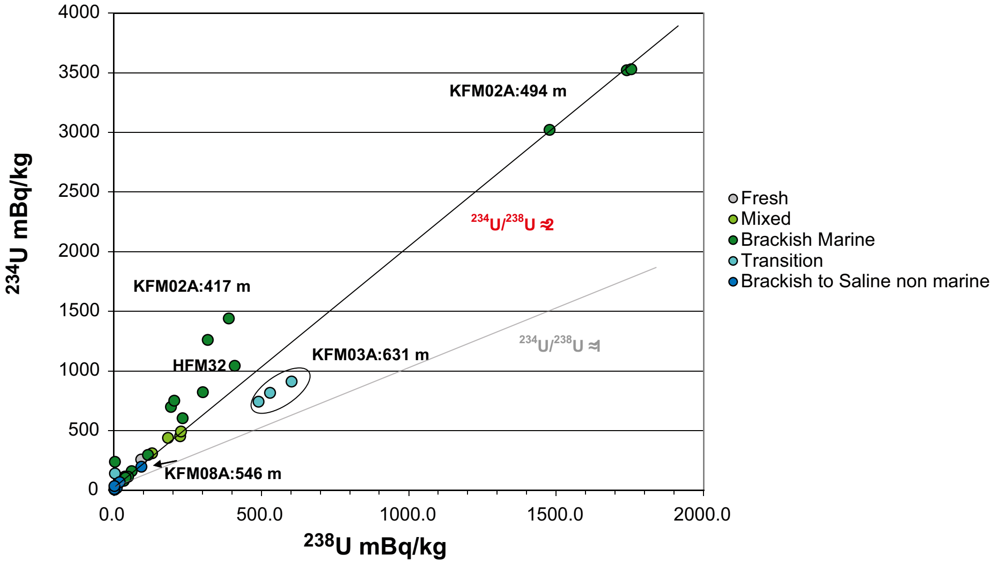


Figure 5-13. *Plot of ^{238}U versus ^{234}U activity for groundwaters from percussion and cored drilled boreholes at Forsmark; only boreholes with elevated uranium contents are indicated. The black line connects samples with lowest $^{234}U/^{238}U$ ratios and all samples are clearly above unity. KFM03A and KFM08A are of special interest and are discussed separately in the text.*

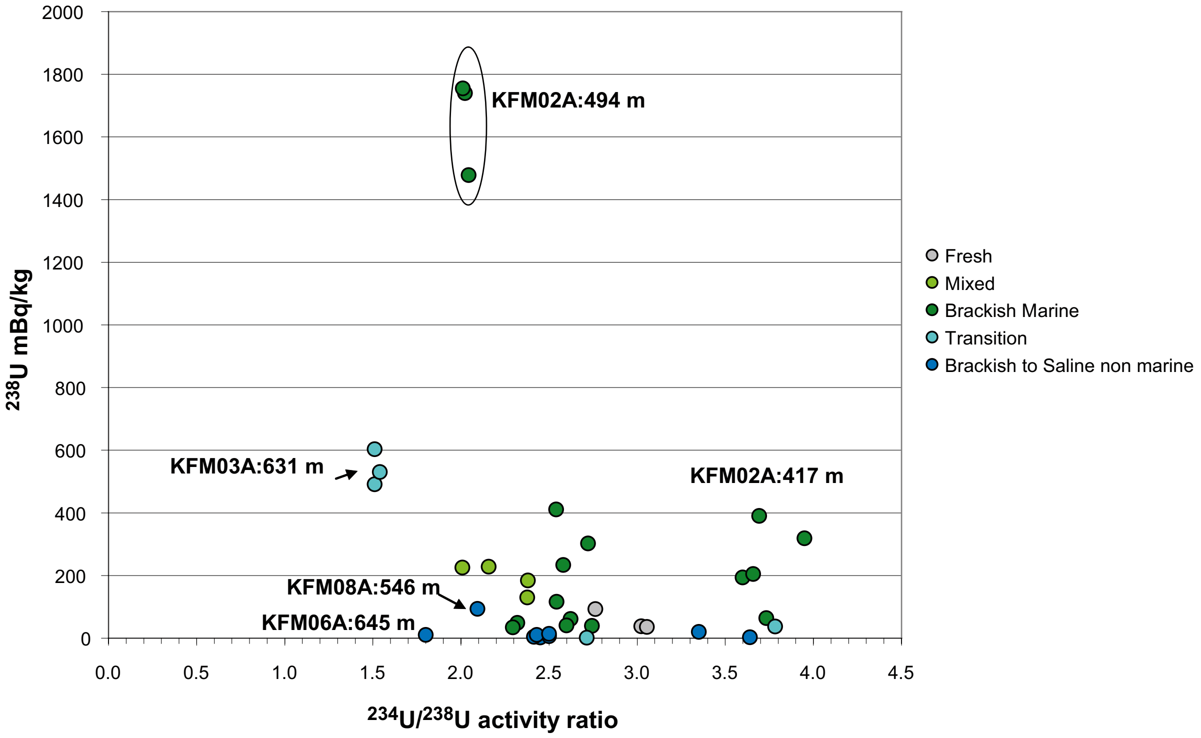


Figure 5-14. *^{234}U/^{238}U activity ratio versus ^{238}U activity (mBq/L) for groundwaters from percussion and cored drilled boreholes at Forsmark; only boreholes with elevated uranium contents are indicated.*

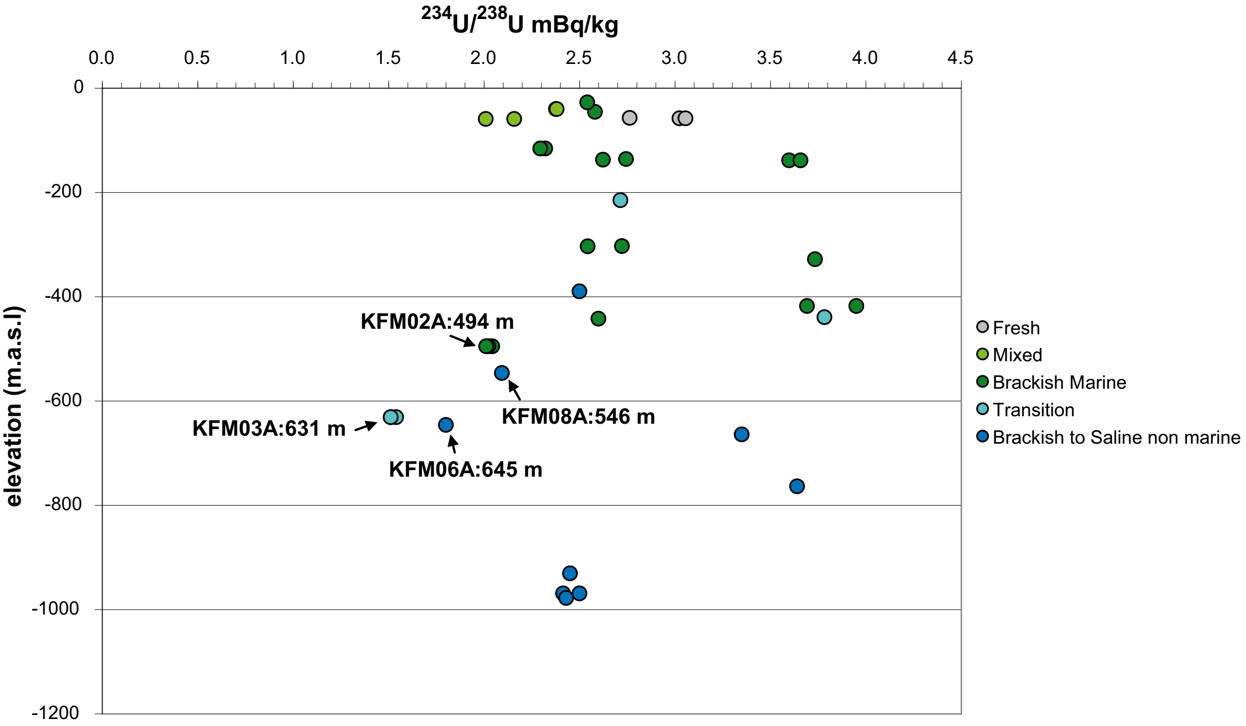


Figure 5-15. *^{234}U/^{238}U activity ratio versus elevation (-m).*

Uranium decay series measurements on fracture coatings

Fracture coatings analysed for uranium series isotopes are all selected to represent open conductive fractures and are, with only a few exceptions, hosted in deformation zones; the results are shown in Table 5-2. However, it can never be assured that the actual sampled part of the fracture coating is in contact with the present-day flowing groundwater, for example, due to channelling. Furthermore, during drilling (e.g. high flushing water under high pressures), subsequent handling of the drill cores (e.g. during mapping and routine testing for calcite in fracture coatings using HCl acid), perhaps intermediate storage in humid conditions, and ultimately during sample preparation, always leads to a degree of uncertainty when interpreting uranium decay series data because of their potential sensitivity to such conditions. At present there is no clear cut evidence that can ensure that one or several of such disturbances have not affected the samples to some degree. However, if the disturbances would have had a significant and consistent effect on uranium, this would have levelled out the original uranium series disequilibria so that the different and versatile characteristics obtained here would not have been observed.

Almost all samples collected from the upper 150 m show disequilibria in one or both of the $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ activity ratios when they are plotted against depth (Figure 5-16). Most of the samples show $^{234}U/^{238}U > 1$ in combination with $^{230}Th/^{234}U$ close to 1, indicating deposition of uranium during the past 1 Ma, or several processes (deposition and removal of uranium) overprinting each other. One sample indicates a possible late (post glacial deposition of uranium) and two samples indicate uranium removal during the same period. One sample at only 20 metres depth sampled in an ENE trending deformation zone in KFM 9B, shows activity ratios close to secular equilibrium, indicating most probably that the sampled part of the fracture has not been conducting water during the last 1 Ma (i.e. an absence of water/rock interaction).

In the same figure, 14 samples from greater depths (300 m and downwards) were analysed and most of these show values closer to secular equilibrium than the near surface samples; six samples show secular equilibrium within ±0.1 and these represent depths from 400 m to 745 m. Eight samples show $^{230}Th/^{234}U$ activity ratios between 1.1 and 1.7 and $^{234}U/^{238}U$ activity ratios close to secular equilibrium. Two samples below 300 m show $^{234}U/^{238}U$ activity ratios ~ 1.3 indicating possible uranium deposition. These samples are from KFM08A at ~ 550 m and KFM8C at ~ 570 m (i.e. both from the target volume).

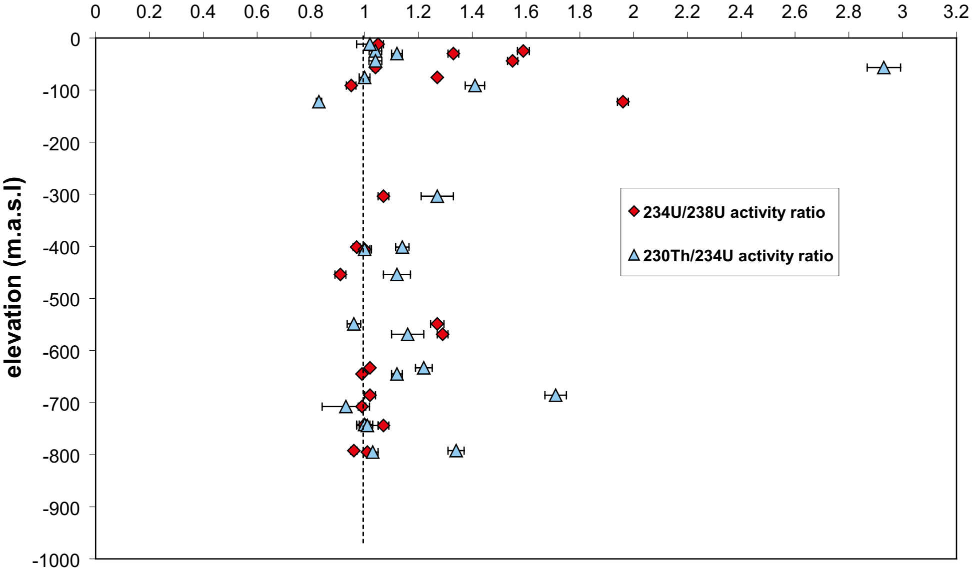


Figure 5-16. *Plots of fracture coating $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ activity ratios versus elevation (m.a.s.l).*

Table 5-2. Thorium, uranium and uranium series data of fracture coating material.

Elevation m.b.s.l.	Sample	Th	U	^{238}U	±1σ	^{234}U	±1σ	^{230}Th	±1σ	^{232}Th	±1σ	^{234}U/^{238}U	±1σ	^{230}Th/^{234}U	±1σ
25.00	KFM01B 28.65–28.70 m	14.10	15.80	201.00	2.3	319	3	331	6.7	66	2.1	1.59	0.022	1.04	0.023
43.86	KFM01B 47.9–48.0 m	5.04	22.10	237.00	2.5	367	3.2	382	8.1	24.2	1.2	1.55	0.019	1.04	0.024
401.27	KFM01B 418.29–43 m	5.31	7.21	72.00	0.68	70	0.67	80	1.6	3.2	0.18	0.97	0.013	1.14	0.025
56.49	KFM03B 65.2–65.25 m	8.07	14.50	174.00	1.3	181	1.3	531	11	47	1.8	1.04	0.011	2.93	0.062
633.14	KFM03 643.8–644.17 m	6.80	2,310.00	25,300.00	374	25,700	380	31,300	656	69	3.8	1.02	0.005	1.22	0.031
792.25	KFM03A 803.85–804.05 m	1.30	3.32	134.00	1.2	129	1.2	173	3.5	26	0.9	0.96	0.012	1.34	0.03
91.21	KFM05A 111.56–111.60 m	9.77	3.25	34.80	0.47	33	0.47	46.5	1	19	0.5	0.95	0.018	1.41	0.036
122.29	KFM06A 145.62 m	2.06	17.80	169.80	1.6	333	2.3	275.1	4.6	112	5	1.96	0.02	0.83	0.01
453.8	KFM06A 622.31 m	n.a.	n.a.	60.50	0.8	55	0.8	61.6	2.4	23.5	1.3	0.91	0.02	1.12	0.05
644.95	KFM06A 770.32 m	14.70	12.80	241.90	1.9	239.1	1.9	268	5.5	926	24	0.99	0.01	1.12	0.02
742.18	KFM07A 896.68 m	< 0.1	2.94	34.90	0.4	35.1	0.4	35	1.2	48.6	1.4	1	0.02	1	0.03
795	KFM07A 968.68 m	n.a.	n.a.	350.30	2.7	354.4	2.7	364.1	6.5	151.6	32	1.01	0.01	1.03	0.02
405.66	KFM08A 495.15 m	0.49	7.97	92.00	1.4	92	1.4	91	1.9	39	0.9	1	0.019	1	0.025
548.81	KFM08A 686.67 m	< 0.1	164.00	1,450.00	24	1,844	27	1,778	38	22	2.3	1.27	0.025	0.96	0.025
707.64	KFM08A 918.84 m	5.88	7.48	283.00	3.3	281	3.3	262	2.5	34	6.6	0.99	0.014	0.93	0.088
29.84	KFM01C 43.0 m	10.20	10.80	83.00	1	111	1	125	2	60	1	1.33	0.02	1.12	0.02
303.61	KFM06A 357.81 m	0.10	14.90	65.00	1	70	1	89	4	31	2	1.07	0.02	1.27	0.06
568.89	KFM08C 683.57 m	2.27	2.61	78.00	1	101	1	118	6	55	4	1.29	0.02	1.16	0.06
685.63	KFM08C 829.94 m	0.68	4.63	69.00	1	71	1	121	2	14	1	1.02	< 0.02	1.71	0.04
744.06	KFM08C 904.06 m	1.44	11.80	109.00	1	116	1	117	4	21	2	1.07	0.02	1.01	0.04
11.97	KFM09B 19.81 m	2.93	5.82	111.00	1	117	1	119	6	20	2	1.05	< 0.01	1.02	0.05
75.53	KFM10A 105.79 m	24.50	24.50	355.00	2	450	2	450	9	16	1	1.27	0.01	1	0.02

In Figure 5-17, the same activity ratios are plotted against uranium contents (^{238}U) showing that ^{230}Th/^{234}U is greater than one and indicating that leaching is possibly more common in samples with low uranium contents up to 180 Bq/kg ^{238}U (i.e. ~15 ppm U). One exception is, however, the fracture coating with the highest uranium content (2,200 ppm) which also shows ^{230}Th/^{234}U >1. ^{234}U/^{238}U activity ratios >1 indicating uranium deposition are usually associated with uranium contents higher than 300 Bq/kg (i.e. ~25 ppm U).

Plots of the activity ratios ^{234}U/^{238}U and ^{230}Th/^{238}U are presented in a standard Thiels diagram in Figure 5-18 /Theil et al. 1983/. This shows that samples from the upper 150 m (labelled red in the figure) plot either in the uranium deposition field or in (or close to) the uranium leaching sector. Samples from greater depths plot closer to secular equilibrium but a number of samples show increased ^{230}Th/^{238}U ratios but with the ^{234}U/^{238}U activity ratios close to one. This is interpreted as the result of a late and rapid single process of uranium mobilisation of (partly?) oxidised uranium present in some of the fractures. Two of the deep samples show, as mentioned above, deposition of uranium during the past 1 Ma (Figure 5-18).

5.3.5 Concluding remarks

Probable deposition of oxidised uranium at repository depth in some of the deformation zones mostly associated with the hanging wall bedrock segment at Forsmark has to be considered. Present studies of the uranium contents and uranium decay series isotopes in both groundwaters and fracture coatings, indicate that part of the uranium has been mobilised during the last 1 Ma, but the uranium enrichment in the fractures is generally older; for example, uranium contents up to 30 ppm are detected in fractures showing uranium isotope secular equilibrium. Significant recent (postglacial) deposition of uranium should have yielded samples with ^{230}Th/^{238}U < 1 which has not been observed in the studied fractures. However, one problem is that only bulk samples have been analysed and small portions of recent (postglacial) deposited uranium can not be distinguished accurately.

The high uranium contents commonly (but not always) associated with the brackish-marine groundwaters, have remained dissolved and have not been deposited in the fractures.

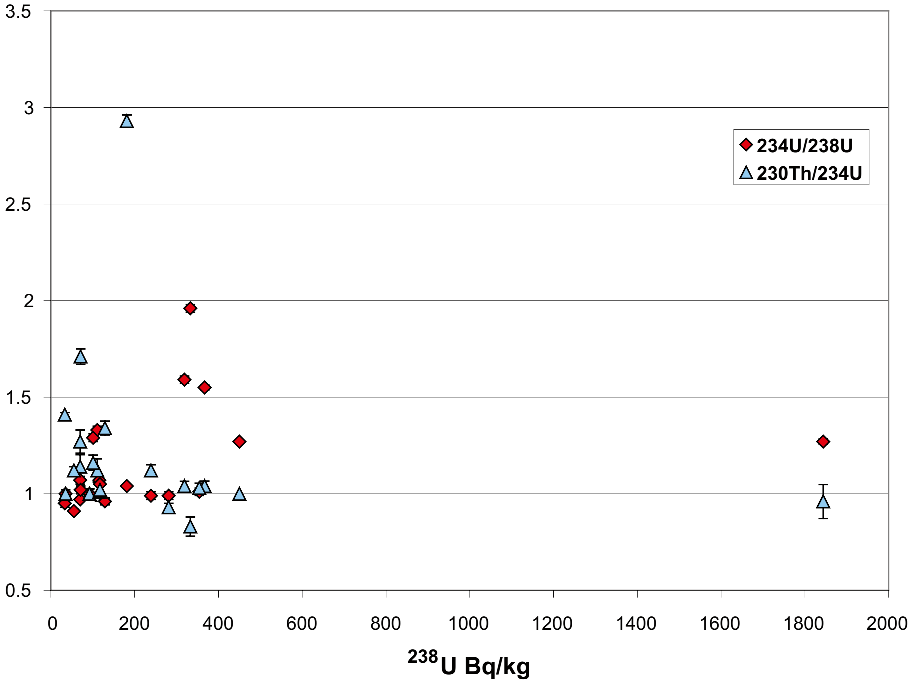


Figure 5-17. Plots of fracture coating ^{234}U/^{238}U and ^{230}Th/^{234}U activity ratios versus ^{238}U activity (similar to U content). Note that sample KFM03A:643.8 m is not included in the plot because of a much higher uranium content (see comments in text).

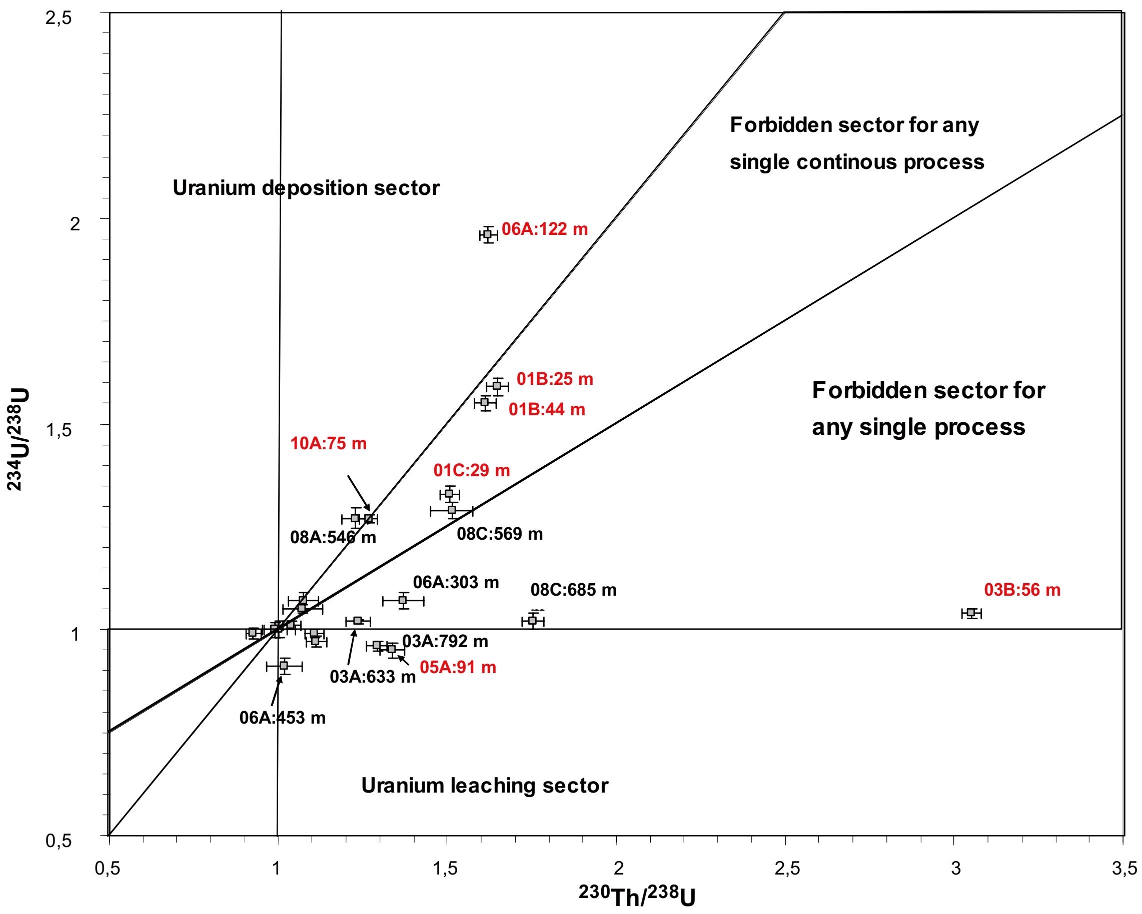


Figure 5-18. $^{234}U/^{238}U$ *activity ratio versus* $^{230}Th/^{238}U$ *activity ratio plot (Thiels diagram) for fracture coating samples from Forsmark. Samples showing disequilibrium (deposition or leaching of U) during the last 1 Ma are labelled. Samples from the upper transmissive 150 m of the bedrock are labelled in red.*

The main conclusions are:

- Deformation zones in the upper transmissive 150 metres of the bedrock show more pronounced deposition and leaching of uranium compatible with a dynamic and heterogeneous groundwater flow system.
- The highest uranium contents in both fracture coatings and groundwaters are found in fractures (all belonging to deformation zones) at depths between 400–700 m. Not only fractures in the most common ESE-WNW orientated gently dipping zones, but also steeply dipping zones orientated ENE and WNW, are represented. It is important to note that at the same depth interval low uranium contents are found in both fracture coatings and groundwater samples indicating the heterogeneity of the uranium distribution.
- The uranium present in groundwaters associated with fracture coatings is dominantly enriched in the oxidised U(VI) state. This may have been introduced into the sampling section (drilling source) or formed in situ by dissolution of a mainly U(VI)-bearing mineral phase(s). From the present understanding of the groundwater system at site the latter explanation is favoured. The earlier indicated possible connection between drilling fluid and uranium content /Appendix A in SKB 2007/ is not supported in the 2.3 groundwater dataset.
- The accumulation of oxidised uranium at around 500 m depth in the hanging wall bedrock segment does not necessarily mean that oxygenated water has penetrated to this depth. Instead, it is shown that that mildly reducing groundwaters with sufficient HCO_3 (>30 mg/L) are capable of keeping U(VI) mobile, and this has resulted in variable accumulations occurring within the fracture zones to maximum depths of around 500 m depth.

- There is direct evidence to show that colloidal uptake has played only a minor role in the mobilisation and transport of uranium /Hallbeck and Pedersen 2008/.
- Microbial activity (possibly enhanced by perturbation in connection with the drilling) may have increased the uranium mobility. For example, it is known that siderophore producing bacteria may affect the mobilisation of radionuclides such as uranium /Kalinowski et al. 2004, Johnsson et al. 2006/ and such bacteria has been identified in borehole KFM08D (L. Hallbeck pers. comm. 2008 ongoing research).
- Dissolved uranium has become concentrated where there is a transition from high to low transmissivity, corresponding to the transition from brackish marine (Littorina) to brackish non-marine groundwaters.
- Generally, the deposition of uranium at depths below 150 m seems not to have occurred primarily during the last deglaciation or subsequent post-glacial groundwater circulation, but partly (documented in five samples) related to groundwater activity during the last 1 Ma.

5.4 Radium and radon

5.4.1 Background

This section contributes to the understanding of the high uranium concentrations in groundwaters at the Forsmark site, described in section 5.3. It also documents and interprets concentrations of radium and radon in these waters and provides further information on the behavior of radium in the environment as a natural analogue to ^{226}Ra that in-grows from uranium in spent fuel over the long term (> 10 ^{5}y).

Elevated uranium concentrations (up to about 145 µg/L) have been found in some Forsmark groundwaters and it has become important to explain this observation in terms of the geochemistry of the Forsmark area and from the point of view of safety assessment. Elevated concentrations of uranium, radium or radon have not been previously encountered during studies of other locations in Sweden, including the Simpevarp/Laxemar areas.

5.4.2 Geochemistry of radium and radon

^{226}Ra (hereonafter referred to as ‘radium’) is the radiogenic daughter of ^{230}Th in the ^{238}U decay chain (Figure 5-19). In natural waters, Ra has a limited solubility and exists mainly as the free ion Ra^{2+}, or the uncharged complex $RaSO_4^0$ /Langmuir and Riese 1985/. Radium is readily removed from solution by absorption on clay minerals and other rock silicates and by coprecipitation with insoluble sulphates. However, it tends to be stabilised in solution by high concentrations of Ca, Na and Cl /Langmuir and Melchior 1985/.

^{222}Rn (hereonafter referred to as ‘radon’) is a noble gas and radiogenic daughter of ^{226}Ra (Figure 5-20). Radon is quite soluble in groundwater and, because of its short half-life (3.82 days) is only found in abundance near to a radon source such as U-enriched minerals in fracture zones or wall-rock. Because it is a gas, it readily moves into solution and, therefore, often far exceeds the concentration of its parent (^{226}Ra).

The standards for maximum levels of uranium and radium in drinking water in Sweden are 100 µg/L and 0.5 Bq/L, respectively. Concentrations of uranium are commonly expressed in terms of mass per volume (µg/L) and of radium and radon as radioactivity (Becquerel) per volume (Bq/L). This convention is used here although uranium may also be given as mBq/L, as radioactivity of the most abundant isotope, ^{238}U, where 1 µg ^{238}U = 12.5 mBq).

In an investigation of 260 private wells, 20% of the wells contained more than 15 µg/L U (information from the Swedish Geological Survey web site: (*http://www.sgu.se/sgu/sv/samhalle/grundvatten/brunnar/radon-brunnsvatten.html*). Unfortunately, there is little information available about the content of radioactive elements such as radium and radon in Swedish drinking water.

5.4.3 Radium

Radium concentrations are generally low in the shallow fresh (soil tube and percussion boreholes) groundwaters (Figure 5-20), but begin to show higher values in the brackish marine groundwaters (up to 500 m depth) and higher still in the deeper, brackish non-marine groundwaters, to 23 Bq/L activity at depths greater than 500 m. As in the case of uranium (see section 5.3), the highest concentrations of radium are found in groundwaters from boreholes KFM02A and KFM03A at intermediate depths (500–650 m) in the hanging wall bedrock. Some moderately high concentrations were also found in borehole KFM07A, located outside the target volume to the north-west of the candidate area, and KFM08A located in the target volume (i.e. footwall bedrock). The marked increase in radium concentrations in the brackish to saline non-marine groundwaters (> 6,000 mg/L Cl) can be clearly see in Figure 5-21, a trend also shown when plotted against by calcium.

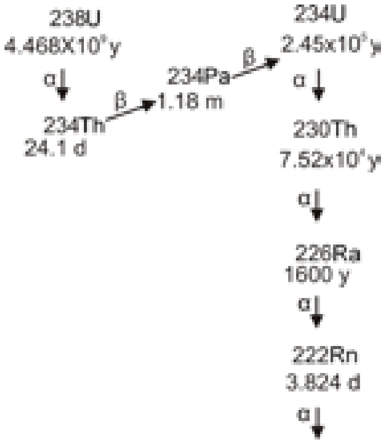


Figure 5-19. *The ^{238}U decay series.*

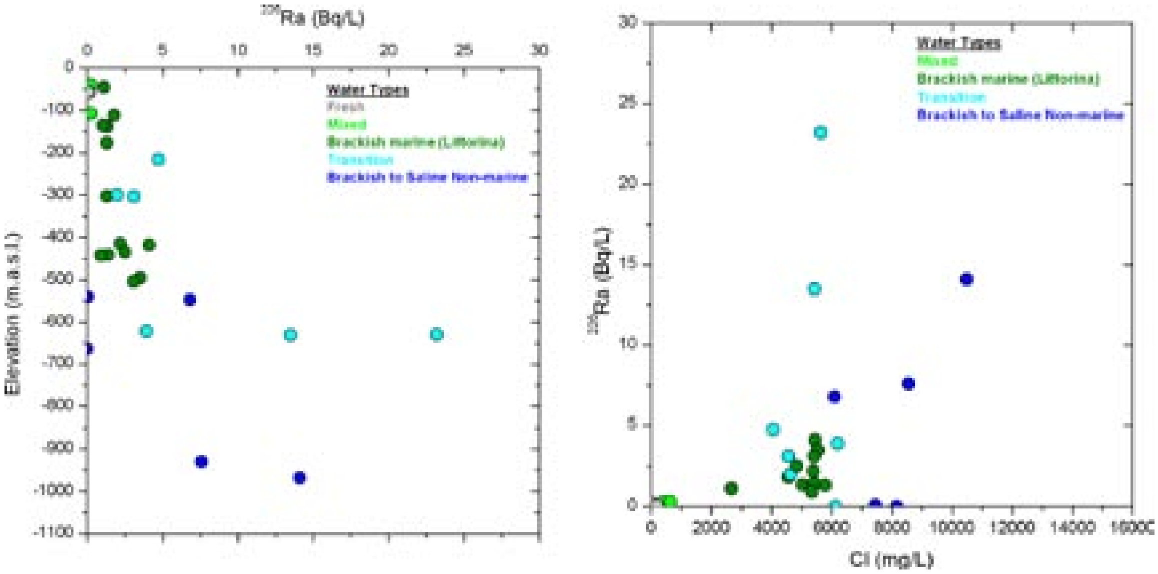


Figure 5-20. *Variation of radium concentration with elevation (left) and with salinity given as Cl (right) in the Forsmark groundwaters.*

Figure 5-21 shows the relationship between uranium and radium content of all groundwaters. It can be seen that while many waters (particularly the shallower groundwaters) have no apparent correlation, deeper groundwaters, if enriched in uranium, are likely to also be higher in radium content, but this is not apparent from the plot. An inverse correlation between uranium and radium might be expected, however, because uranium concentration normally decreases (due to lower redox potential and lack of HCO_3) as salinity increases, whereas radium is not affected directly by redox and tends to form soluble complexes as salinity increases. This is, however, not shown by the plotted data.

5.4.4 Radon

Radon concentrations in Forsmark groundwaters range between 0 and 3,500 Bq/L activity (i.e. a maximum of almost 0.1 µCi/L). The variation with elevation and with salinity (as Cl) is shown in Figures 5-22 and 5-23, respectively.

Radon concentrations are almost all well in excess of the level for secular radioacive equilibrium with radium. In fact, the excess may be as high as two orders of magnitude. Once again, there is a prominent peak of radon in the depth and salinity plots but there is no clear relationship between radon and radium concentrations (Figure 5-24). Such a correlation might be expected because radium is the immediate parent radionuclide to radon and localised enrichments of radium in the host rock or wall rock would act as a source of radon that would diffuse into the adjacent groundwater.

5.4.5 Summary and conclusions

Radium activity concentrations are fairly low in the shallow groundwaters but increase in the deeper groundwaters to 23 Bq/L activity, well above drinking water limits (0.5 Bq/L). The radium and radon contents of Forsmark groundwaters show only limited correlations with parameters such as depth, chloride and uranium contents.

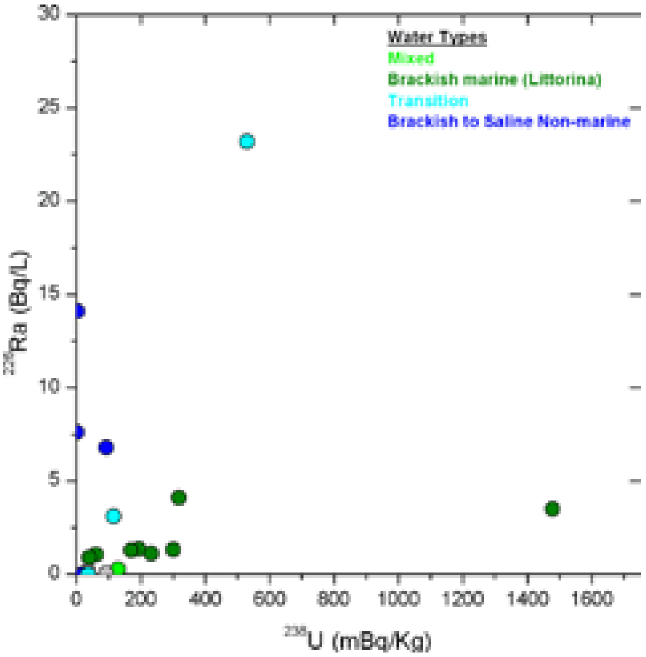


Figure 5-21. *Variation of Ra with U in the Forsmark groundwaters*

It is also interesting to note that based on different mechanisms, the locations of high radium and radon values also coincide with highly permeable fracture zones in the bedrock, i.e. the hanging wall bedrock segment, which will allow more of the radon inventory to escape into solution than in the case of relatively unfractured rock. This is supported by studies of U, Ra and Rn at the site of the Underground Research Laboratory in Manitoba, Canada, where exactly the same characteristics were observed.

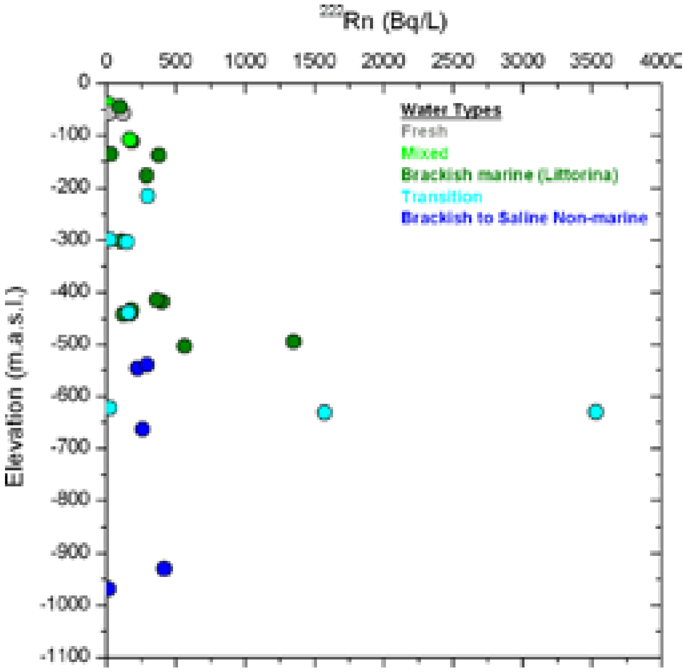


Figure 5-22. *Variation of radon with elevation in the Forsmark groundwaters.*

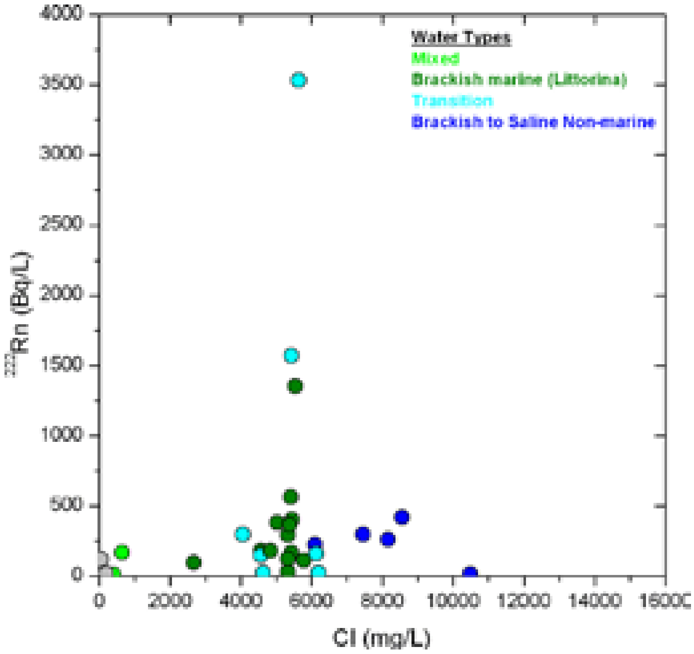


Figure 5-23. *Variation of radon with salinity (as Cl) in Forsmark groundwaters.*

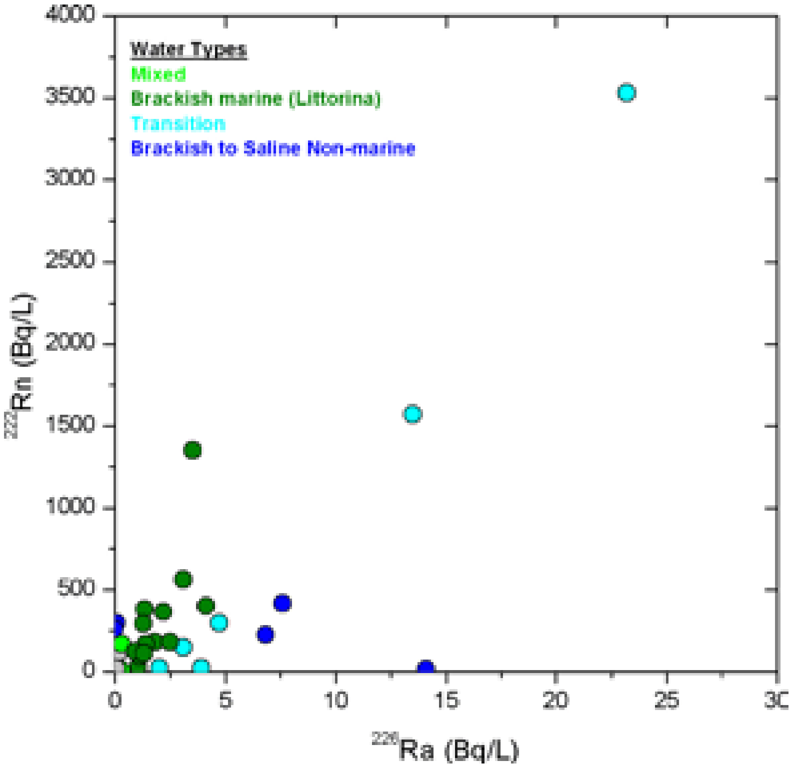


Figure 5-24. *Relationship of radon with radium in Forsmark groundwaters.*

5.5 Sulphur and its variability in groundwaters and bedrock

Quantitative information on the sulphur system (mainly comprising sulphate and sulphide in groundwater and minerals) is important for the site descriptive modelling for two primary reasons: 1) The sulphur system plays an important role in controlling the Eh in groundwaters from intermediate to greater depth /Gimeno et al. 2008/. 2) Sulphide production, which normally is the result of sulphate-reducing bacteria (SRB) activity, can jeopardise the long term stability of the copper canister by corrosion.

Below, available information on sulphate and sulphide contents and sulphur isotopes ($\delta^{34}S_{(SO4)}$) in analysed groundwater samples from percussion and cored boreholes at Forsmark are discussed. In addition, the information on occurrences of sulphur-bearing minerals (mainly from the Boremap logging and detailed work reported in /Sandström et al. 2008/) is commented upon when relevant.

In most cases sulphate constitutes the largest sulphur pool in the groundwaters and may have very different origins depending on the groundwater history. The main sources in fresh waters are usually the result of atmospheric deposition and oxidation of sulphides or dissolution of sulphates in the overburden. Any water of marine origin (e.g. Baltic Sea and Littorina Sea at Forsmark) initially carries elevated sulphate contents with a specific isotopic signature ($\delta^{34}S_{(SO4)}$) when entering the bedrock. However, both content and isotopic signature may later be modified. Brackish and saline waters at greater depths with long residence times in the bedrock have sulphate contents of mixed origins, such as marine sources, interactions with solid phases (e.g. dissolution of sulphate-bearing minerals), or sulphate from very old brine waters (potentially sedimentary brines). The sulphate contents may also be modified by permafrost freeze-out processes (i.e. formation and dissociation of mirabilite, although no evidence of this has been found), and in most cases sulphate-reducing bacteria.

5.5.1 Sulphate

In order to give an overall picture of the sulphate variation all groundwater samples, except for tube samples and samples with > 15% drilling fluid, have been plotted against elevation in Figure 5-25. Despite the large variation, the Fresh, Brackish marine and Brackish to Saline non-marine groundwater types have been distinguished clearly in the plots, as well as mixtures between dominantly marine and fresh waters (Mixed waters) and samples including Brackish marine and non-marine components (named Transition). It is evident that the brackish marine waters have the highest sulphate contents, whereas fresh waters and brackish to saline non-marine types are dominated by low sulphate contents. When plotting the same dataset versus chloride content (Figure 5-26) a possible slight increase in sulphate content with increasing chloride content for the saline non-marine waters is indicated. This is, however, very uncertain and only based on sampling from two boreholes sections (KFM07A and KFM09A) which are located outside the target volume. From Figures 5-25 and 5-26, it is obvious that the major source of sulphate is marine and mainly associated with the brackish marine water of Littorina type, and to lesser extent in the upper part of the bedrock with a possible present Baltic Sea water contribution.

Stable sulphur isotope ratios, expressed as δ^{34}S CDT (Canyon Diablo Troilite), have been determined in sulphate from surface waters and groundwaters. Considering the shallow waters, /Tröjbom et al. 2007/ have made a thorough evaluation of the possible origins of sulphur in the surface water system. It was concluded that atmospheric deposition and oxidation of sulphides in the soil cover constitutes the most important sources, together with marine sulphate.

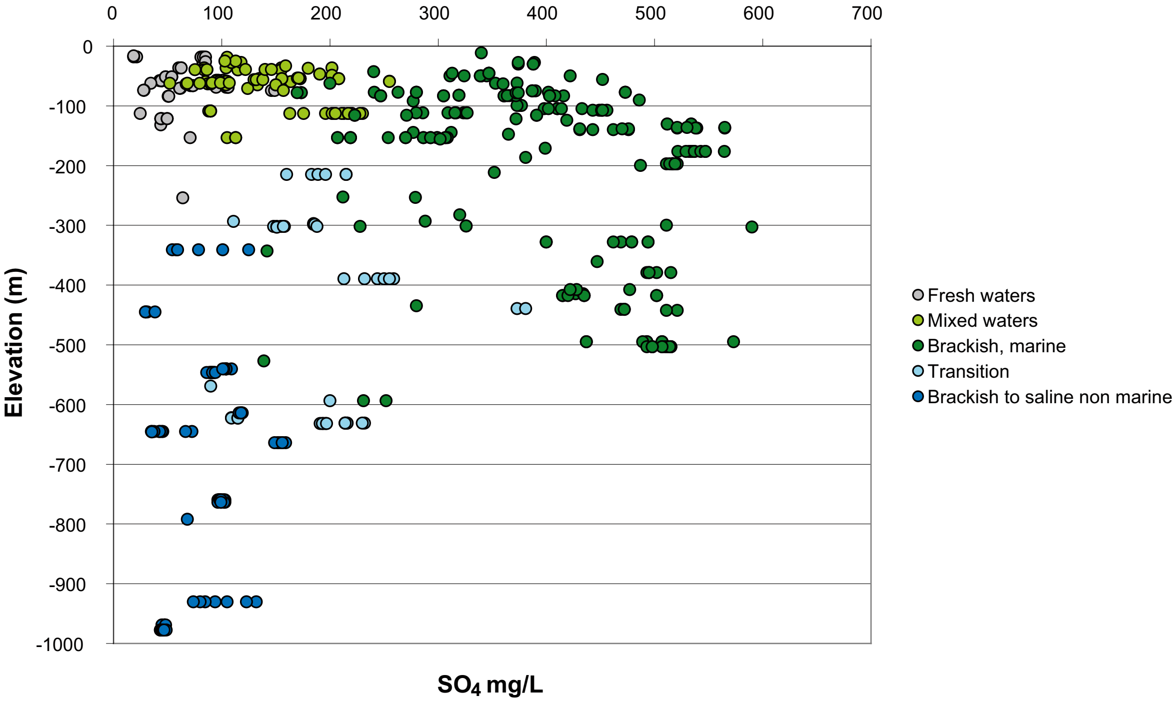


Figure 5-25. *SO_4 groundwaters from percussion and cored boreholes from the Forsmark area plotted versus elevation. A horizontal sequence of time-series measurements for some samples is indicated. Not included are tube samples and samples with > 15% drilling fluid.*

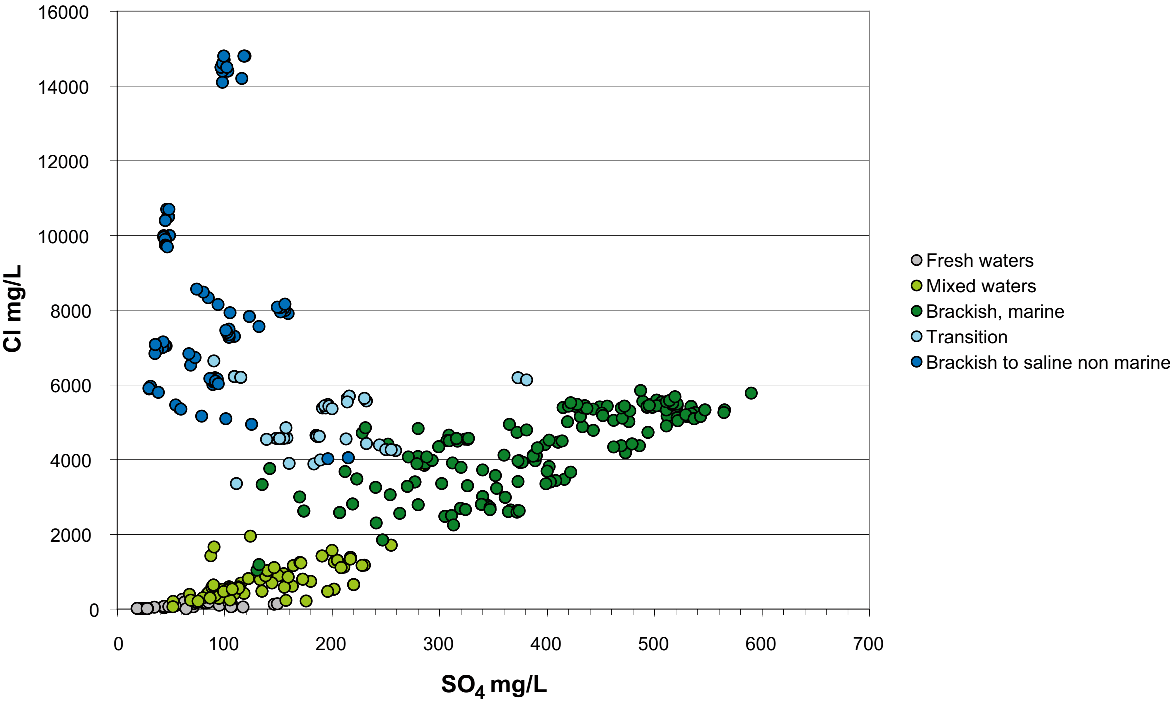


Figure 5-26. *Cl versus SO_4 contents for different groundwaters types at Forsmark. Not included are tube samples and samples with > 15% drilling fluid.*

To better describe possible mixing trends, the sulphur isotope ratios $\delta^{34}S_{(SO4)}$ plotted against chloride content is shown in Figure 5-27, and 1/SO_4 versus $\delta^{34}S_{(SO4)}$ in Figure 5-28. The fresh waters show low sulphate contents and a large variation in $\delta^{34}S_{(SO4)}$ compatible with input from several different sources of which oxidised sulphur from sulphides in the soil cover may be one /Tröjbom et al. 2007/. Unfortunately, there are no isotopic analyses of sulphides in the overburden, but $\delta^{34}S$ values of pyrites in fracture coatings have been analysed and show a very large spread in values (5.4 to 31.5‰ CDT with the majority of samples showing values < 17‰ CDT /Sandström et al. 2008/).

The dominating sulphur mineral in the fracture system is pyrite. Sulphur isotope analyses of fracture coating pyrite (cf. section above) support a biogenic origin potentially suggesting the possibility that pyrite is a young phase. Detailed studies reported in /Sandström et al. 2008/ show, however, that most of the observed pyrite shows a clear association with the Palaeozoic generation of fracture mineralisations, and is associated with very small amounts of galena. In groundwater systems the Fe^{2+} contents will put an upper limit to the S^{2-} contents by the stability of different Fe-sulphide phases, primarily FeS_{am} and/or pyrite /Gimeno et al. 2008/.

Most of the brackish marine waters show relatively homogeneous $\delta^{34}S_{(SO4)}$ values around 26‰ CDT irrespective of sulphate content (Figure 5-28). This is a somewhat higher sulphur isotope ratio than expected since the original values for the Littorina Sea are supposed to be in accordance with the present seawater value ($\delta^{34}S_{(SO4)}$ ~21‰ CDT /Clarke and Fritz 1997/). Sulphate reduction during closed conditions produces enrichment of the heavier ^{34}S in the sulphate, and in such cases $\delta^{34}S_{(SO4)}$ is expected to correlate inversely with the sulphate content. This is observed for some of the marine waters, but most of them show a relatively stable isotope signature between 24–26‰ CDT which may be interpreted as an influence of sulphate reduction during open to partly closed conditions. It is important to note that none of the brackish marine waters have preserved their original marine SO_4/Cl ratio (~ 0.14 weight ratio). This may be partly due to mixing with other waters but, as suggested by the $\delta^{34}S_{(SO4)}$ signature, mostly by sulphate reduction. On going sulphate reduction is documented and sulphate-reducing bacteria have been identified at depths greater than 320 m in all but one of the boreholes sampled for microbes /Gimeno et al. 2008/.

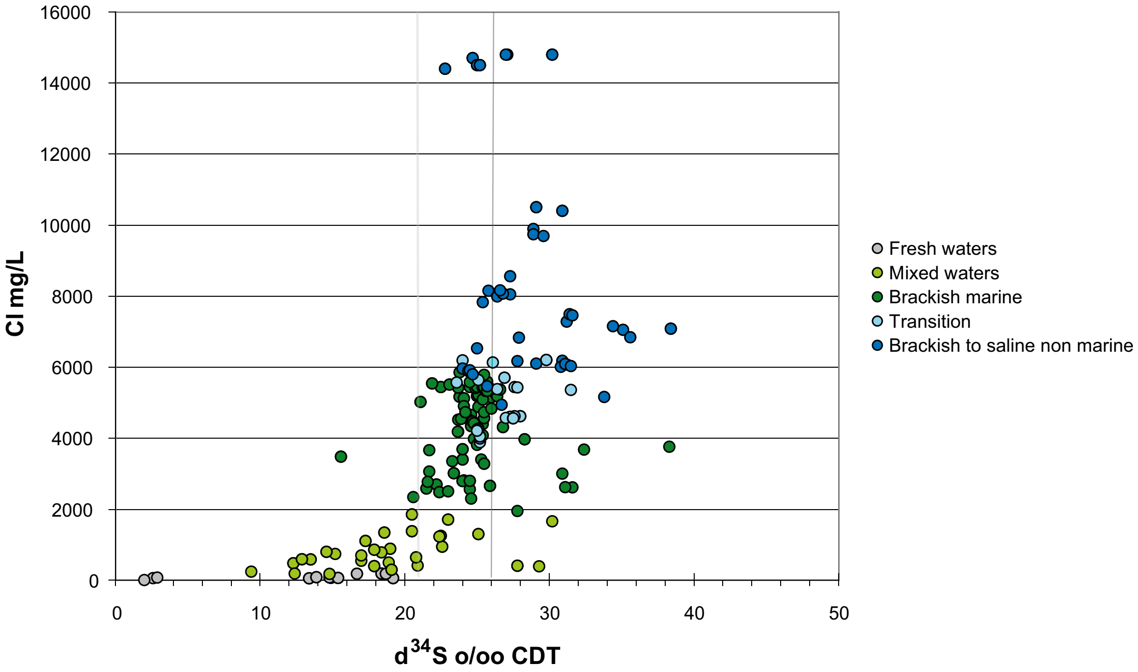


Figure 5-27. Cl versus $\delta^{34}S$ (CDT) for different groundwaters types at Forsmark. The marine value (around 21‰ CDT) is indicated by the light grey vertical line and the dark grey line signifies the upper limit for the majority of the brackish marine (Littorina) groundwaters. Not included are tube samples and samples with > 15% drilling fluid.

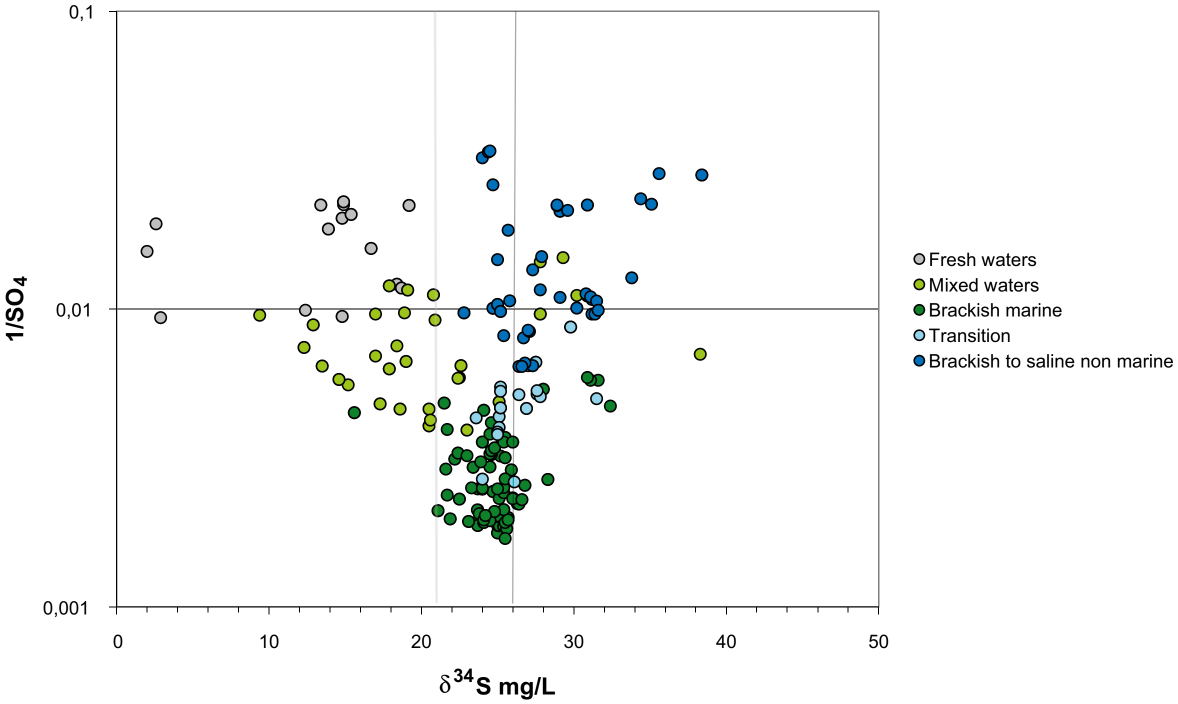


Figure 5-28. $\delta^{34}S$ versus $1/SO_4$ in surface waters and groundwaters from Forsmark. The marine value (around 21‰ CDT) is indicated by the light grey vertical line. Not included are tube samples and samples with > 15% drilling fluid.

The brackish to saline non-marine waters show generally low sulphate contents and high $\delta^{34}S_{(SO4)}$ values (≥ 26‰ CDT). This is a strong indication of modification caused by sulphate reduction; however, the consumption of sulphate seems to stop at sulphate contents around 30–40 mg/L for unknown reasons. No major additional sulphur source in these waters can be identified, which means that the bedrock aquifer at depth is, in general (at Forsmark), a low sulphate environment. This is also supported by the fracture mineralogy that shows almost an absence of sulphate minerals with the exceptions of a few microscopic grains of barite.

5.5.2 Sulphide

Sulphide has been measured in groundwaters from the cored boreholes during the complete chemical characterisation (CCC) programme (Figure 5-29). These values are generally low (< 0.1 mg/L for the majority of samples) but show a slight increase with depth and a correspondence between sulphide and the number of sulphate-reducing bacteria has been indicated /Hallbeck and Pedersen 2008/.

During the groundwater monitoring programme a number of isolated borehole sections have been revisited and sampled twice a year (a few sections had already been sampled on four occasions). It has been shown that some sections show much higher (but usually variable) sulphide contents during the monitoring phase than was recorded during the CCC sampling programme. Figure 5-30 shows a plot of all sulphide values sampled during the CCC and monitoring phases (note the different scales compared with Figure 5-29). Values >0.5 mg/L have been recorded in five of the monitoring sections and values >1 mg/L in two sections. Other sections in contrast, show low and stable sulphide contents.

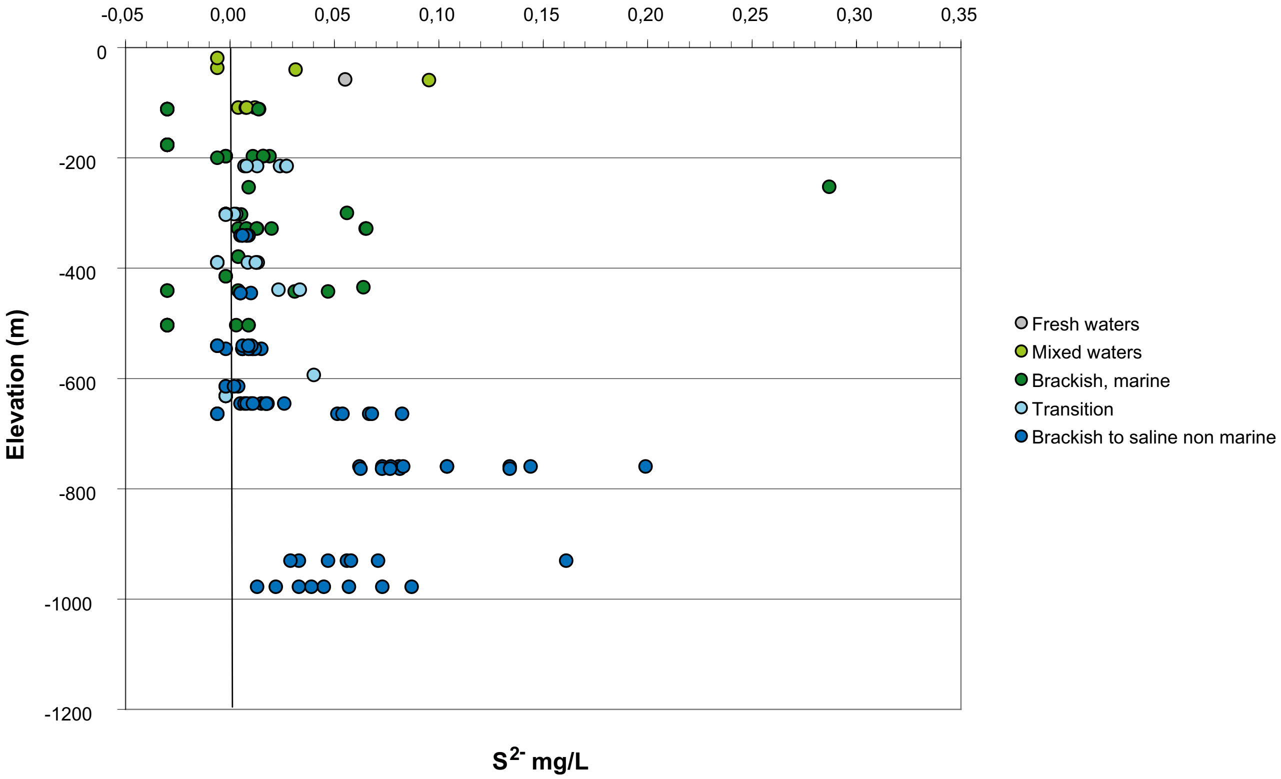


__Figure 5-29.__ Sulphide versus depth for all samples from CCC sampling. A horizontal sequence of time-series measurements for some samples is indicated.

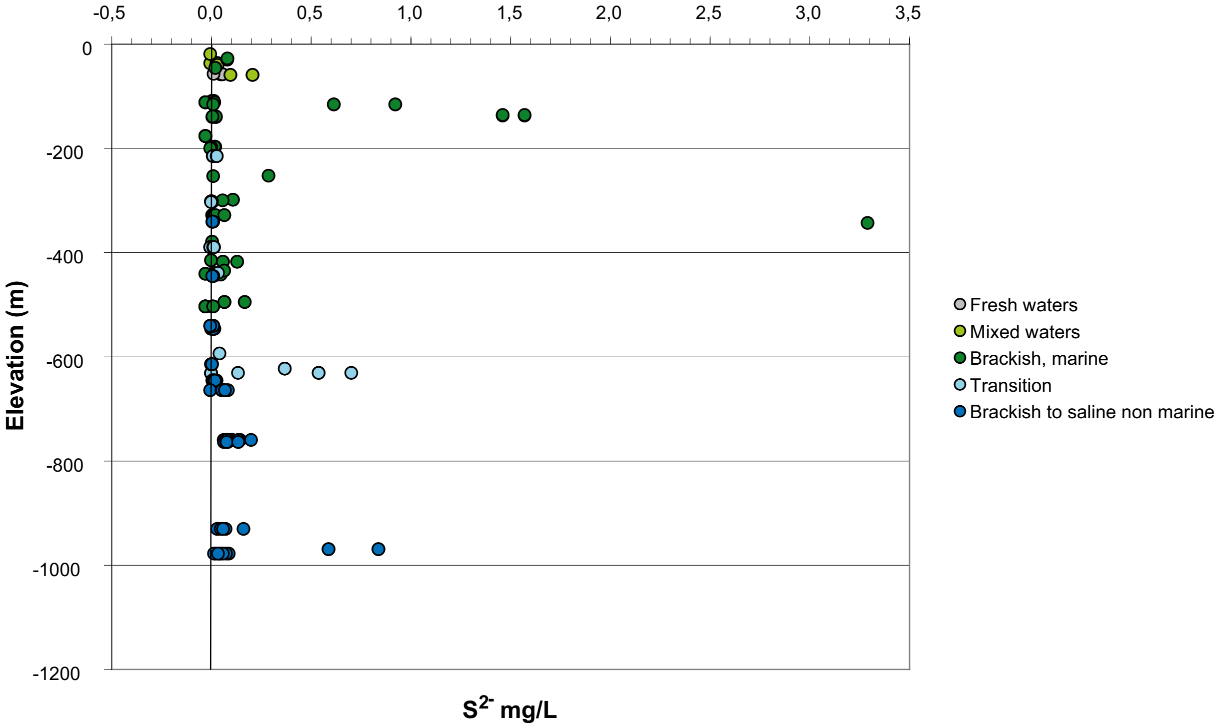


Figure 5-30. *Sulphide versus depth for all samples. Not included are tube samples and samples with > 15% drilling fluid.*

Several explanations for the high and varying sulphide contents can be suggested, of which the two most contrasting are:

a) The initial low values recorded in the boreholes during the CCC programme are largely representative, and the increased values during the monitoring sampling is a result of anthropogenic mixing and increased energy supply to the microbes. Anthropogenic mixing has been suggested from other trace element studies (cf. sections 5.2 and 5.3).

b) The high values during the monitoring are closer to being representative because the SRB are very sensitive to high flow rates resulting in a lowering of microbial activity. Disturbances caused by the drilling and subsequent pumping therefore may have lowered the initial sulphide production significantly. Such responses have been demonstrated at Äspö by /Pedersen 2005b/.

It is also possible that neither the low initial values nor the high values recorded during the monitoring are representative as the system may need a much longer time to recover since initial drilling activities. Only the forthcoming sampling campaign can provide answers, in particular closer attention to adequate time-series sampling data.

5.5.3 Conclusions

1) The major sulphur source in the Forsmark groundwaters is marine in origin, in particular due to the intrusion of Littorina Sea water.

2) Sulphate reduction mediated by SRB has decreased the sulphate content in the marine waters and modified their original $\delta^{34}S_{(SO4)}$ values. This has occurred during partly open conditions (e.g. modification of the Littorina Sea water relatively close to the surface or in large pools of sea sediments which has not been entirely closed). At greater depth sulphate reduction during closed conditions has resulted in very low sulphate contents and correspondingly high $\delta^{34}S_{(SO4)}$ values (>30‰ CDT). SRB are also indicated as active at depth in the Forsmark groundwaters /Hallbeck and Pedersen 2008/.

3) Measurements of sulphide at different sampling occasions have yielded very different results and continued sampling is needed before more detailed interpretations should be attempted.

4) No major additional sulphur source in the deep groundwaters (which are generally low in sulphate) can be distinguished, which means that the bedrock aquifer at depth represents, in general, a low sulphate environment.

5.6 Phosphate, nitrate, nitrite and ammonium

5.6.1 Phosphate

Phosphate concentrations (PO_4^{3-}) in the Forsmark groundwaters are very low. The maximum concentrations of around 0.1 mg/L are even lower than those detected in other crystalline environments like Simpevarp, Olkiluoto /Pitkänen et al. 2004/ or Lac du Bonnet Batholith, Canada /Gascoyne 2004/.

As in these systems, the highest variability and contents of dissolved PO_4^{3-} in the Forsmark area are associated to the near surface groundwaters (with maximum values near 0.1 mg/L) and some very shallow fresh and mixed groundwaters also show relatively higher concentrations (from 0.015 to 0.065 mg/L). Phosphate concentrations in deeper groundwaters are always below 0.05 mg/L, or even below the detection limit (Figure 5-31).

The higher concentrations found in the near surface and fresh shallow groundwaters are probably related with the decomposition of organic matter in the overburden or in the recharge zone.

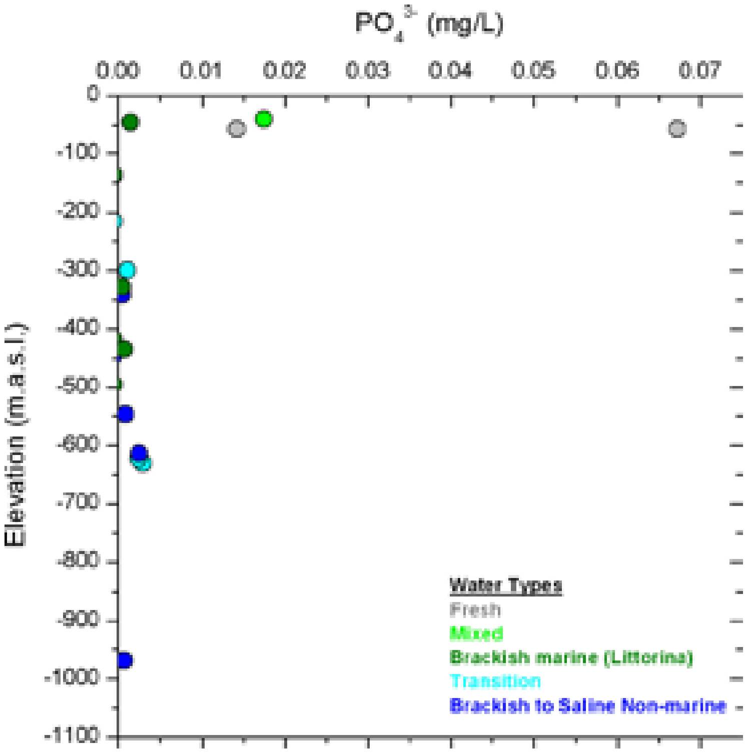


Figure 5-31. *Plot of PO_4^{3-} versus depth.*

5.6.2 Nitrate, nitrite and ammonium

Analytical data for dissolved nitrogen oxidation states include NO_2^-, NO_3^-, $NO_2^- + NO_3^-$, NH_4^+ and N_{total} in the near surface groundwaters (soil pipes). In the groundwater samples N_{total} has not been measured.

Nitrate, nitrite and ammonium concentrations show the largest variability and highest concentrations in the near surface groundwaters, reaching values up to 0.48 mg/L for nitrate, 0.02 mg/L for nitrite and 8.7 mg/L for ammonium. Nitrate and nitrite contents are mostly at trace level as it usually occurs in natural (non-contaminated) systems /Appelo and Postma 2005/. The major part of the total nitrogen usually occurs as ammonium or dissolved organic nitrogen /Tröjbom and Söderback 2006/, showing a temporal variability as they are affected by seasonal variation in the biological activity /Berg et al. 2006/.

As it occurs in other crystalline environments (e.g. in the granitic batholith from Lac du Bonnet, Canada /Gascoyne 2004/), dissolved nitrite and nitrate concentrations in the Forsmark groundwaters are very low (even lower than in near surface groundwaters) and many samples are below the detection limit. The maximum concentrations are around 0.0015 mg/L for nitrite and 0.006 mg/L for nitrate (Figure 5-32).

The dissolved NH_4^+ shows a very different path from that of NO_2^- and NO_3^-. Although the highest concentrations are also found in the near surface groundwaters (with values up to 9 mg/L), high values are also found in the groundwaters (almost 2.5 mg/L) even at 500 m depth (Figure 5-33).

The highest NH_4^+ concentrations (between 1 and 2.5 mg/L) are systematically associated to brackish marine (Littorina) groundwaters (Figure 5-33) with chloride concentrations between 5,000 and 5,500 mg/L. This association also occurs in Olkiluto groundwaters) where groundwaters with high Littorina contribution (with chloride contents between 3,000 and 5,000 mg/l) also show variable and high NH_4^+ concentrations (with maximum values near 0.9 mg/L; /Pitkänen et al. 2004/). In the Simpevarp groundwaters, with minor contribution of Littorina, NH_4^+ concentrations are always lower than 0.5 mg/L and, most of them, near or below the detection limit.

All these observations indicate that the high NH_4^+ concentrations found in the groundwaters from Forsmark represent an inherited character from their old marine signature. Sea water show very low NH_4^+ concentrations (usually well below 0.05 mg/L in the available samples from the Baltic sea). In marine sediments containing organic matter, bacterial activity promotes the transformation of organic nitrogen compounds and the formation of NH_4^+ /Pitkänen et al. 2004 and references therein/.

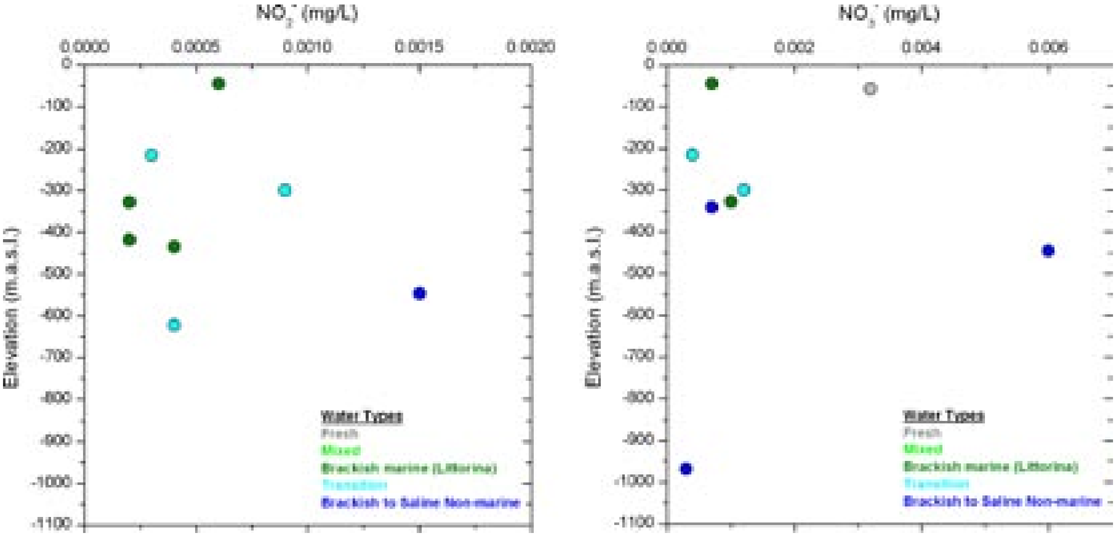


Figure 5-32. *Plot of nitrite (left) and nitrate (right) versus elevation.*

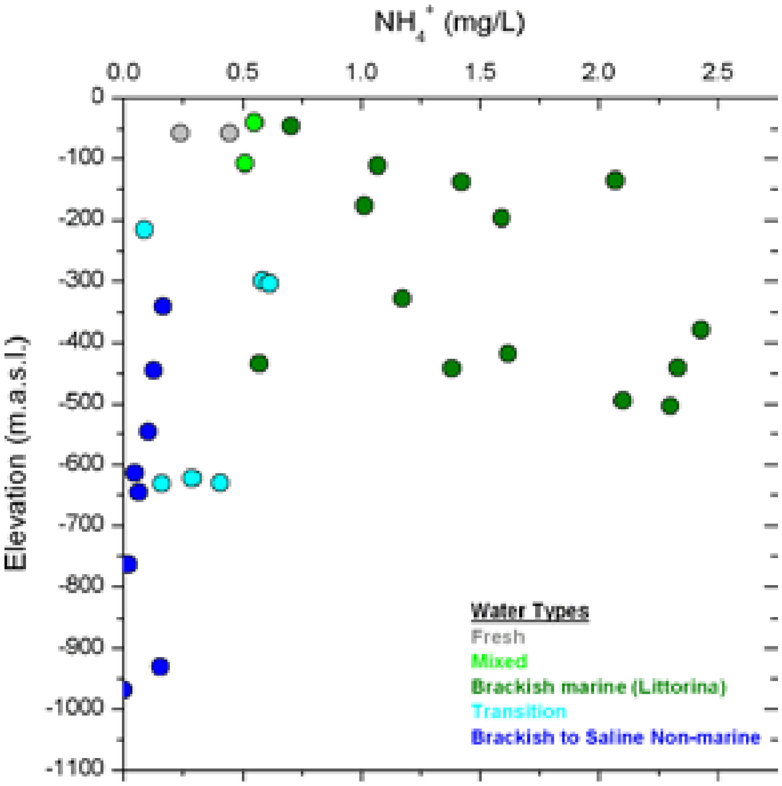


Figure 5-33. *Plot of ammonium versus elevation.*

Increasing ammonium concentrations with depth in the interstitial waters from marine sediments is a common observation. It occurs also in the present sediments of the Baltic Sea, where concentrations from 4 to 16 mg/L are frequent /Carman and Rahm 1997/. Therefore, infiltration of the recharging Littorina waters through marine sediments can easily justify important increments in dissolved NH_4^+.

Cation exchange processes can produce significant decreases in NH_4^+ concentrations /Appelo and Postma 2005/ during circulation of these marine waters through the fractured bedrock. However, these reaction processes have not been able to completely mask the marine signature. Moreover, reducing conditions preclude the (bacterial) nitrification of ammonium /Appelo and Postma 2005/ and, therefore, favours the presence of NH_4^+ in the groundwaters.

In the brackish to saline non-marine groundwaters, NH_4^+ concentrations are very low, always below 0.25 mg/L (Figure 9-3). Only transition groundwaters show higher concentrations, but below 0.5 mg/L.

5.7 Permafrost

5.7.1 Background

Under cold desert conditions permafrost formation is expected to precede the build-up and movement of a continental ice mass during the next glacial period in Fennoscandia, some 120,000 years from now /SKB 2006c/. This will cause the bedrock groundwaters to be frozen gradually to unknown depths, but perhaps to 400–500 m based on present day observations in northern Canada and elsewhere /Gascoyne 2000, Ahonen 2001, Ruskeeniemi et al. 2004/ and supported by predictive palaeohydrogeological modelling /Boulton et al. 2001, SKB 2006c/.

The permafrost will subsequently decay and disappear when it is gradually overridden by the movement of the (warm-base) continental ice sheet, and water circulation in the upper bedrock will once again become established. At a much later stage, following the maximum extent of glaciation, temperatures will begin to increase and the ice sheet will undergo degradation and retreat accompanied by the release of large volumes of meltwater into the bedrock. Due to high pressure hydraulic gradients these deglaciation meltwaters are suspected to have recharged to depths of at least 1 km into the bedrock, based on isotopic evidence (i.e. depleted $\delta^{18}O$ values).

Both permafrost and deglaciation may influence, therefore, the hydrochemical character of the bedrock groundwaters to repository depths, which in turn may influence the long-term safety and performance of the repository system.

5.7.2 Freeze-out processes

The incremental freezing of surface water and bedrock groundwater ahead of the advancing continental ice sheet is believed to give rise to the formation of near-surface 'freeze-out' brines, possibly propagating down to several hundred metres. Permafrost may be accompanied also by an upward migration of old, deeper saline groundwaters to shallower levels. This may occur in open talik environments (i.e. periodically or permanently unfrozen river and lake systems) where groundwater discharge movement to the surface occurs by the vertical transfer of heat energy /Pidwirny 2006/. A recent review of permafrost and its effect on bedrock hydrochemistry is given by /Gascoyne 2000/; some aspects are also presented in /SKB 2006a, section 14.3/. Implications to the Swedish bedrock have been described and discussed in and /Chapter 4 in SKB 2006c/ and the system modelled and discussed in /Vidstrand et al. 2006/.

Concept

According to /Bein and Arad 1992/ the formation of permafrost in a brackish lake or a restricted coastal sea environment (e.g. similar to the Baltic Sea or Hudson Bay in Canada) produced a layer of highly concentrated salinity ahead of the advancing freezing front. This is based on the fact that when water freezes slowly, most of the solutes present in the water will not be incorporated in the crystal lattice of the ice. During this process, salts that have been present in the surface waters and groundwaters will tend to accumulate at the propagating freeze-out front. This front is, however, not necessarily sharp, because freezing probably will take place over a range of temperatures, depending on the salinity and on the ratio between 'free' and tightly adsorbed water molecules. Since this saline water would be of high density, it subsequently would sink to lower depths (i.e. density intrusion), would avoid dilution by oceanic water, and potentially penetrate into the bedrock where it would eventually mix with formational groundwaters of similar density. However, whether the volume of high salinity water produced by this freeze-out process would be adequate to produce such widespread salinity effects deep in the bedrock as observed in the Fennoscandian basement, is presently under debate and is discussed further in section 5.10.

Where the bedrock is not covered by brackish lake or restricted sea water, similar freeze-out processes would occur in the bedrock on a much smaller scale within the hydraulically active fractures and fracture zones, again resulting in formation of a higher density saline component which would gradually sink and eventually mix with existing saline groundwaters at depth. /Zhang and Frape 2003/ and /Ruskeeniemi et al. 2004/ point out that freeze-out processes can only increase the salinity when the initial formation groundwaters are also saline. This means that such processes will occur mainly at depths below the fresh meteoric water recharge environment which will dominate the upper bedrock. Furthermore, the incremental downward propagation of the freeze-out front will eventually cease due to increased salinity, increased temperature and a decrease in transmissivity which will hinder potential pathways for the residual fluids.

During permafrost decay and subsequent deglaciation, these residual saline waters may escape mixing and flushing effects because of entrapment in low transmissive parts of the bedrock, for example, in dead-end pathways, microfractures, lenses or pockets, or in the rock matrix itself as distinctive porewater compositions. Fortuitous drilling may intersect such reservoirs that could reveal hydrochemical and/or isotopic evidence of a permafrost freeze-out origin to the released groundwaters.

From another angle, some of the dilute waters resulting from permafrost decay may have been involved in the formation of mineral phases (e.g. calcite) along fracture surfaces. However, could such calcites (or their fine zonations) be distinguishable (if they could survive) from calcites formed during the deglaciation phase or even from present-day type meteoric conditions?

Laboratory experiments

The freeze-out hypothesis described above is largely based on laboratory freezing experiments (e.g. /Nelson and Thompson 1954/, cf. discussion in /SKB 2006a/) which were able to distinguish between the products of evaporation and freezing. The solid products from evaporation consisted of halite with subsidiary gypsum, and from freezing, hydrahalite and mirabilite. The most important difference during freezing is the removal of the SO_4^{2-} ion in mirabilite ($Na_2SO_4 \cdot 10H_2O$). Present day evidence of freeze-out processes might therefore include the possible preservation of mirabilite or, most likely, a sulphate-rich lens or pocket of groundwater because of the highly metastable nature of mirabilite to temperature increase. To date, no anomalous sulphate-rich groundwaters have been recognised from the Swedish investigated sites. One promising occurrence at the Palmottu natural analogue site in Finland subsequently has been interpreted as being hydrothermal in origin based on sulphur isotope data /Smellie et al. 2002/.

A laboratory study involving $\delta^{37}Cl$, $\delta^{18}O$ and $\delta^{2}H$ was carried out as part of the Lupin Mine permafrost project in northern Canada. This study entailed the controlled freezing of Canadian and Fennoscandian Shield groundwaters to assess the importance of geochemical and isotopic signatures in recognising and interpreting freeze-out effects in palaeogroundwaters /Ruskeeniemi et al. 2004/. Representing the Fennoscandian Shield were Na-SO_4 groundwaters from Palmottu, suspected to have been derived from freezing (referred to above), and from the Canadian Shield a Ca-Cl brine from Sudbury which, according to /Herut et al. 1990/, may have been produced by freezing. Both column (for a slower rate of freezing) and batch (faster rate freezing) experiments were carried out at the University of Waterloo /Zhang and Frape 2003, Ruskeeniemi et al. 2004/.

The laboratory experiments showed that there was a successive enrichment of $\delta^{18}O$ and $\delta^{2}H$ in the ice during freezing; this agreed with the predicted behaviour of the Palmottu groundwater sample using fractionation factors reported in the literature. The behaviour of $\delta^{37}Cl$ was less relevant because the freeze-out data mainly reflected that of the free chloride, i.e. the chlorine signature of the residual solution.

Isotopic indicators in groundwaters

Suggested isotopic indicators of freeze-out processes should include therefore $\delta^{18}O$ and $\delta^{2}H$ (and possibly $\delta^{37}Cl$,) based on the experiments described above. In addition, /Casanova et al. 2005/ discuss the potential use of $\delta^{11}B$ based on a study of Fennoscandian groundwaters.

The experimental work of /Ruskeeniemi at al. 2004/ suggested that groundwaters subjected to extended permafrost conditions may result in heavier $\delta^{18}O$ and $\delta^{2}H$ (and possibly $\delta^{37}Cl$) values in the solid ice phase and depleted values in the residual groundwater phase. If preservation of such residual groundwaters has occurred, for example, in low transmissive parts of the bedrock, then possibly they may be detectable if suitable resevoirs are tapped into and successfully sampled. In the Forsmark area a suitable candidate borehole is KFM01D which intersects several low transmissive, single discrete fractures. The deepest section sampled at 445.17 m vertical depth records a $\delta^{18}O$ of –10.5‰ SMOW and a $\delta^{2}H$ of –67.5‰ SMOW; these values can be compared to the next deepest section at 340.87 m vertical depth which records values of

–11.1‰ SMOW and –76.9‰ SMOW respectively. Both of these sampled sections, in particular the deeper one, record stable isotope values significantly more enriched than the surrounding more accessible brackish non-marine formation groundwaters which range from approximately –13.8 to –11.5‰ δ^{18}O and –98.5 to –81.7‰ δ^{2}H. Of course such trends of stable isotope enrichment with depth can be explained also by long term water/rock interaction and/or porewater diffusion processes under decreasing flow to stagnant conditions. Furthermore, down to around 300 m in the same borehole there has been an ingress of groundwater with a weak Littorina Sea component (partly anthropogenic) which also could have enriched the stable isotope signal to some extent. These alternative possibilities, especially within that depth interval where permafrost conditions probably have been active (to around 500 m), underlines the difficulty of identifying with certainty any periglacial effects.

A more global approach has been that of /Casanova et al. 2005/ who studied groundwaters from the Äspö HRL in Sweden and several sites in Finland using boron and its isotopes: a) to establish the degree of water/rock interaction, b) to assess groundwater mixing, and c) to clarify freezing processes. This is made possible by the large relative mass difference between the isotopes ^{10}B and ^{11}B and the high chemical reactivity of boron; this causes significant isotope fractionation resulting in large variations in the ^{11}B/^{10}B ratios in natural samples.

With respect to freezing processes, /Casanova et al. 2005/ suggest that the permafrost process would be accompanied by the preferential fractionation of ^{10}B into the ice component and ^{11}B into the fluid phase. Although subsequent melting of the ice would mix with the residual fluid, and additional mixing with different groundwater incursions would also eventually occur with time, these modifications may be restricted to the more highly transmissive parts of the bedrock, whilst low transmissive parts may have preserved freeze-out fluids enriched in ^{11}B (similar to that postulated for the enriched stable isotopes discussed above).

In Figure 5-34 /Casanova et al. 2005/ show the relationship of δ^{11}B vs. depth and δ^{11}B versus δ^{18}O for Fennoscandian groundwaters, Baltic Sea waters and the Mean Sea Water field (MSW). The Äspö and Palmottu samples exhibit a similar pattern to that of Olkiluoto and Hästholmen,

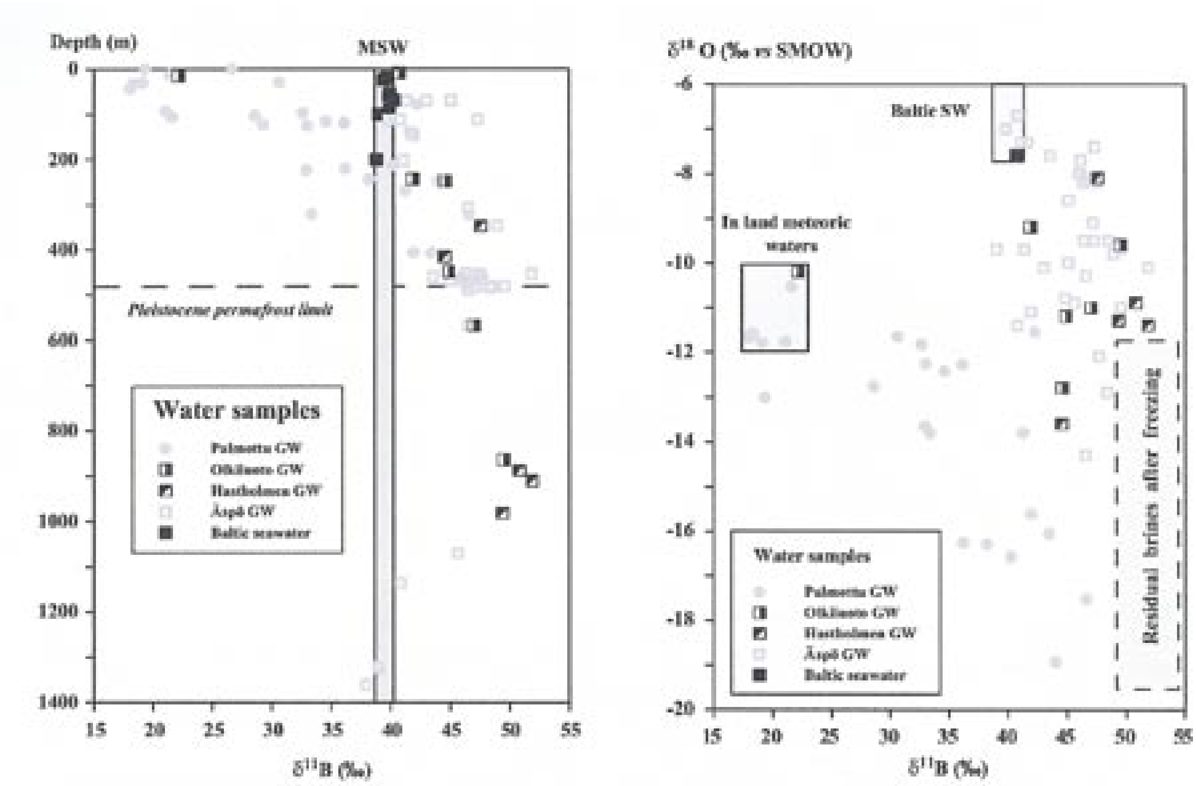


Figure 5-34. *δ^{11}B values as a function of depth (left figure) and δ^{11}B versus δ^{18}O (right figure) for Fennoscandian groundwaters, Baltic Sea waters and the Mean Sea Water field (MSW) /after Casanova et al. 2005/.*

i.e. a tendency for δ^{11}B enrichment with depth and δ^{11}B enrichment correlated with depleted δ^{18}O. These trends have been interpreted as suggesting the general presence of a freeze-out signature at depths greater than 400–500 m. The trend to depleted δ^{11}B values at greatest depths (> 1,200 m) reflect the transition to highly saline groundwaters in borehole KLX02 which represent 'stagnant' groundwater conditions and therefore are unlikely to have been influenced by freeze-out processes.

To test this approach, plots of boron and δ^{11}B vs. elevation, δ^{11}B vs. δ^{18}O and δ^{11}B vs. δ^{37}Cl for the Forsmark groundwaters are presented in Figures 5-35 and 5-36. The only obvious trend is an increase in boron with depth, but this is not shared by δ^{11}B. Furthermore, there is no systematic enrichment of δ^{11}B that correlates with increased depletion of δ^{18}O, or is there any enrichment of δ^{37}Cl when plotted against δ^{11}B, which also may be a sensitive parameter to groundwater freezing processes /Frape et al. 1996, Pitkänen et al. 2004/. Furthermore, contrary to Olkiluoto there is no relationship between enriched δ^{37}Cl and depleted δ^{18}O (Figure 5-37), which might have been expected in groundwaters influenced by freezing during periglacial times.

Collectively, the application of isotopes sensitive to freezing processes have not produced any convincing evidence that such processes have occurred in the Forsmark area, even though freezing during permafrost conditions has been likely. Much of the present data are ambiguous, for example, water/rock interaction processes at increasing depth might also explain some of the observed data distribution, although not the very high values. /Casanova et al. 2005/ draw attention to the fact that the Fennoscandian Shield groundwaters record the highest δ^{11}B values, even higher than the Canadian Shield (commonly enriched by water/interaction processes), suggesting the selective uptake of δ^{10}B into ice related to freezing processes, and leaving residual fluids rich in δ^{11}B.

The absence of depth relationships in the Forsmark area (e.g. maximum δ^{11}B at around 500 m, the limit of Pleistocene permafrost), as suggested in some of the other Fennnoscandian sites by /Casanova et al. 2005/, may reflect the complex hydrogeology of the Forsmark site, where the shallow bedrock aquifer influencing the footwall target area limits recharge below around 200 m depth. In the hanging wall segment, where there are more dynamic conditions to 500–600 m depth, any residual δ^{11}B signature may have been disturbed by the incursion of different water types and subsequent mixing processes since the last deglaciation. For example, just taking the brackish marine (Littorina) groundwaters in the plots presented above, there are still no convincing trends. Furthermore, sampling artefacts causing some scattering of data observed for other trace components cannot be ruled out totally for boron and its isotopes either (cf. sections 5.2 and 5.5).

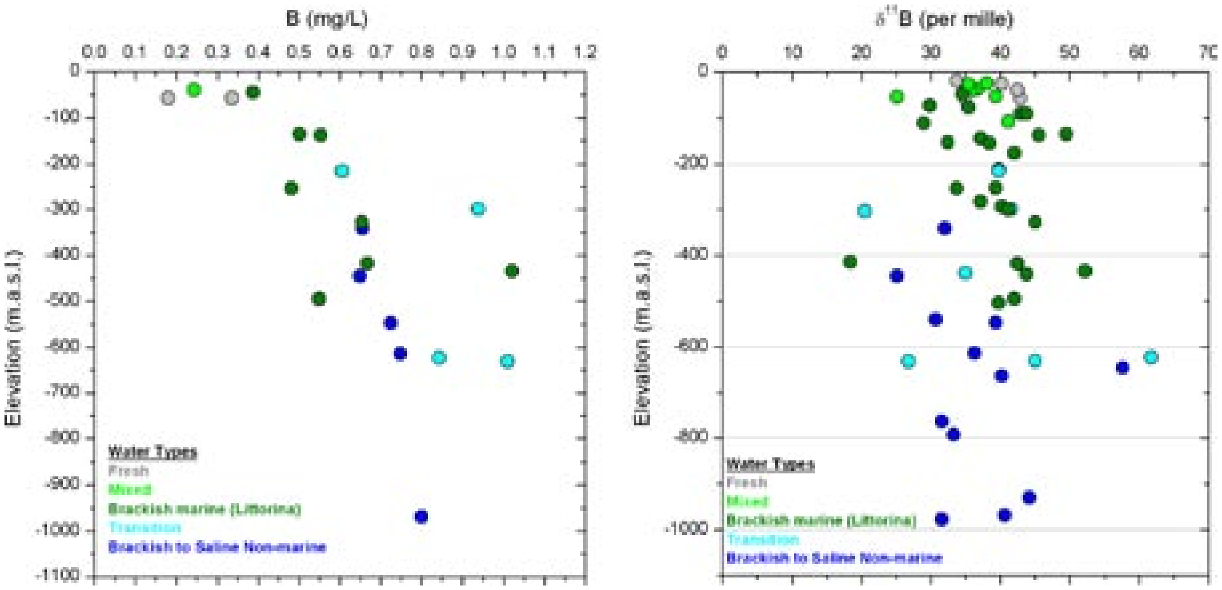


Figure 5-35. *Plots of boron vs. elevation and δ^{11}B vs. depth for the Forsmark area groundwaters.*

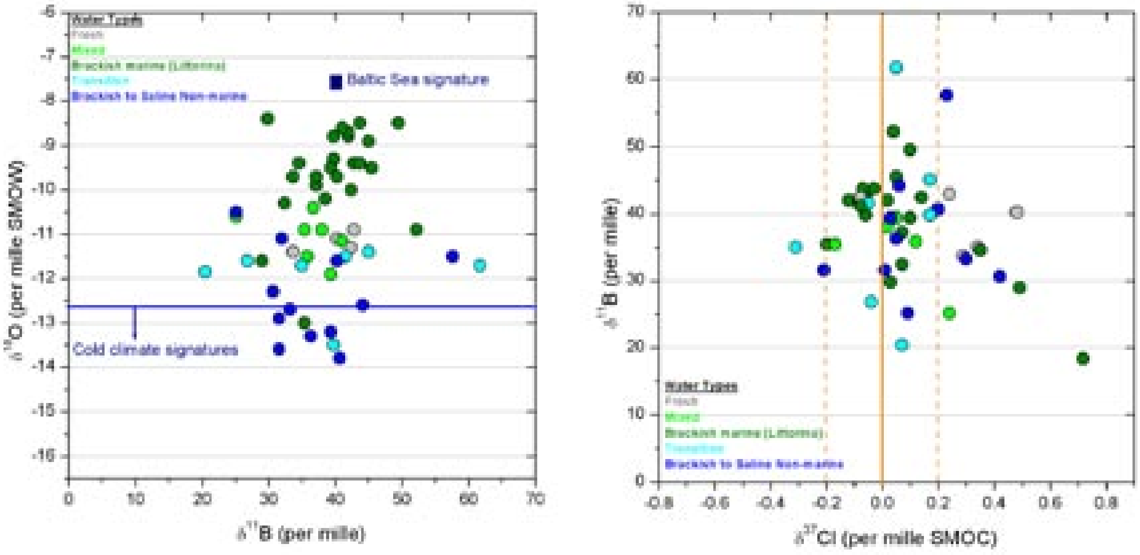


Figure 5-36. *Plots of $\delta^{11}B$ vs. $\delta^{18}O$, and $\delta^{11}B$ vs. $\delta^{37}Cl$ for the Forsmark area groundwaters.*

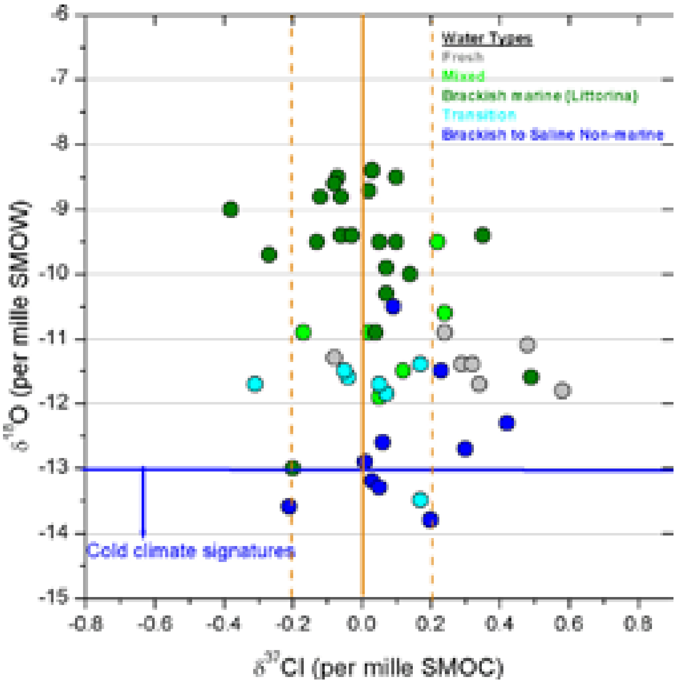


Figure 5-37. *$\delta^{18}O$ versus $\delta^{37}Cl$ for Forsmark groundwaters. Dashed brown line indicates ± 0.2‰ $\delta^{37}Cl$ analytical uncertainty.*

Alternative options

The possibility of producing deep brines from seawater freezing along the margins of continental ice masses has been proposed by /Starinsky and Katz 2003/. This was tested in laboratory freezing studies /e.g. Herut et al. 1990/ where sodium, chloride and bromide were used to differentiate between the formation of brines from evaporation and freezing processes. For example, ‘during freezing sodium is first removed from the brine as mirabilite ($Na_2SO_4 \cdot 10H_2O$) at about –8°C reflecting a concentration factor of about ×4, followed by hydrohalite ($NaCl \cdot 2H_2O$) at a concentration factor around ×10. During evaporation, though, sodium is removed only as halite, as of and above a 10-fold concentration’. By plotting $(Na/Cl)_{eq}$ against $(Br/Cl)_{eq}$ ×100 should differentiate therefore between a cryogenic and evaporative origin to the Ca-chloride brines of the Canadian and Fennoscandian Shield environments.

The Forsmark groundwaters are presented in Figure 5-38 which shows the old, brackish to saline non-marine groundwaters plotting close to the cryogenic curve. Because the brackish marine (Littorina) groundwaters have not been subject to freezing processes, they are not relevant to this present discussion. Based on this figure, the initial reaction is that the remaining data appear to be quite convincing. However, it may also indicate that other processes may have produced the good match, i.e. similar processes that can explain the positions of the shallower brackish marine groundwaters.

Generally there are inconsistencies to this theory of sea water freezing. For example, /Pitkänen et al. 2003/ point out that the high salinities associated with many of the Finnish brine-type groundwaters are sensitive to lithological variations, indicating that water/rock interaction over very long time periods (minimum 1.5 Ma; section 5.10) is a significant process. It is therefore doubtful that sea water feeezing initiated during the Quaternary can be the sole explanation to deep brine chemistry.

Isotopic indicators in fracture fillings

During the freezing of water containing dissolved calcium and bicarbonate, degassing of CO_2 can give rise to so-called cryogenic carbonate deposits /e.g. Lacelle et al. 2006/. What evidence, if any, can be extracted from the systematic fracture filling calcite studies carried out in the Forsmark area /Sandström et al. 2008/.

Carbonates in the form of fracture filling calcites occur throughout the Fennoscandian bedrock and their stable isotopes and trace element compositions have been used as indicators of past and present hydrogeological conditions due to their relative fast response to changes in fluid chemistry and temperature etc /e.g. Peterman and Wallin 1999, Blyth et al. 2000, Milodowski et al. 2005/.

In conclusion, although there is the possibility that some calcites have formed under cold climate conditions in the upper approximate 200 m of bedrock at Forsmark, there is no direct evidence that such formation occurred during freeze-out of bedrock groundwaters under permafrost conditions However, calcites with a clear glacial signature have not been detected yet (cf. section 6.5).

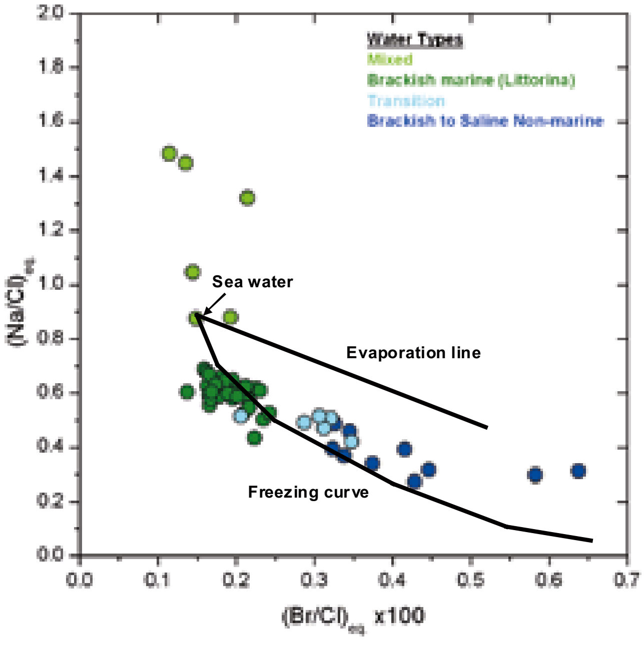


Figure 5-38. *Na/Cl versus Br/Cl for Forsmark groundwaters. Freezing curve and evaporation line are based on Herut et al. 1990 /after Starinski and Katz 2003/.*

5.7.3 Summary and conclusions

- Laboratory studies show that surface to near-surface freezing of groundwater can produce a residual fluid of high salinity and, because of its high density, may migrate along hydraulically active fractures and settle at depth in the bedrock.
- Freezing during permafrost has probably occurred in the Fennoscandian Shield and climate modelling has indicated likely penetration to depths of 400–500 m or more, i.e. at least to repository levels.
- Propagation of a freezing front down into the bedrock may force the residual fluid into low transmissive areas adjacent to the main transmissive pathways, i.e. dead-end pathways; microfractures; rock matrix porewater chemistry etc.
- These low transmissive 'traps' are the most promising source of undiluted residual fluids and therefore may provide the best evidence of freeze-out processes. To date, no evidence has been indicated by the porewater studies at Forsmark.
- The residual fluids should not only be characterised by high salinities, but may also have enriched signatures of $\delta^{18}O$, $\delta^{2}H$, $\delta^{11}B$ and possibly $\delta^{37}Cl$.
- These isotopes in combination have been applied to the groundwaters sampled at Forsmark and used to search for evidence of freezing during periglacial times. Collectively, they have not produced any strong evidence that freeze-out processes have occurred, with the exception of unusually high $\delta^{11}B$ signatures which are a common feature in the Fennoscandian Shield.
- The absence of isotopic trends may also reflect the complex hydrogeology of the Forsmark site, in particular the limiting effect of the shallow bedrock aquifer to downward penetration of recharging waters (or freeze-out residual brines).
- Some of the freeze-out theories to brine formation have been tested. Whilst there is some apparent support for seawater freezing, it is doubtful that it can be the sole explanation to deep brine formation. Water-rock processes over very long time periods play a significant role, imparting specific chemical lithological signatures to the groundwaters.
- The incursion of different water types and subsequent mixing processes since the last deglaciation have, in all probability, diluted or mixed to varying degrees many of the relevant isotopic groundwater signatures that may have existed. Furthermore, fracture filling calcites may have been precipitated or dissolved at various stages, or maybe still retain evidence of palaeoevents in the form of fine coatings or zones too small to quantify.

5.8 Brackish marine (Littorina) groundwaters

The brackish marine (Littorina) groundwaters at Forsmark penetrated the bedrock by density intrusion, mixing with resident groundwater mixtures of last deglaciation meltwaters at shallow depths, and at greater depths with increasingly more brackish groundwaters formed from old mixtures of meteoric, glacial and deeper saline groundwaters dating from before the last deglaciation (cf. section 6.7). Recent meteoric recharge waters have entered the upper bedrock contributing an extra component to the mixing processes. In addition, different reactions have taken place, including microbially mediated reactions and water/rock interaction (e.g. ion exchange). During the hydrochemical evaluation the complexity of these brackish marine groundwaters quickly became evident. For example, despite their limited chloride values (2,000 to 10,000 mg/L), very large variations in sulphate, bicarbonate, magnesium and potassium contents, and also in element ratios like Na/Ca (cf. Figures 7-9 to 7-11 in section 7.24) and Br/Cl, are charactersitic. Furthermore, the stable isotope composition shows a wide variation from –14 to –7‰ V-SMOW. To simplify evaluation and understanding, it was decided to subdivide these groundwaters into groups reflecting different origins and residence times.

The old saline water, as well as brackish marine waters of Littorina type that have contributed to the resulting brackish groundwaters, are very common from 100 m down to 300 m or 600 m depending on the location (i.e. footwall or hanging wall bedrock respectively). In addition, these waters may have been diluted by fresh waters of very different ages and origins (including cold and temperate climates). This mixing becomes apparent when the entire 2.3 groundwater dataset, including the SFR samples and the present Baltic Sea samples from outside the Forsmark area, is plotted using a standard δ^{18}O versus Cl plot (Figure 5-39). Several mixing trends can be revealed;

- Present meteoric waters are mixed with modern Baltic Sea in the near surface bedrock environment.
- Littorina Sea samples show a dilution trend indicating mixing with a depleted δ^{18}O water of glacial meltwater origin, probably largely originating from the last deglaciation.
- The Littorina Sea-glacial mixture in turn is mixed with older, deeper brackish to saline waters of non marine origin.

It is obvious that including the SFR samples contributes significantly to the identification of the brackish marine Littorina Sea water. The SFR samples are generally representing the upper 200 m of the footwall bedrock (i.e. mainly fracture domain FFM02), but that part of the bedrock beneath the Baltic Sea. From a hydrogeological perspective, this must be the best place to find the most distinct Littorina signatures preserved.

Section 2.1.3 in /Gimeno et al. 2008/ summarises the discussion and the relevant references concerning the probable maximum salinity and corresponding δ^{18}O‰ signature of the original Littorina Sea. Values of 6,100–6,500 mg/L Cl and –4.5 to –5‰ δ^{18}O V-SMOW appear to be a common estimate. From the plot of δ^{18}O versus chloride (Figure 5-39) it can be seen that

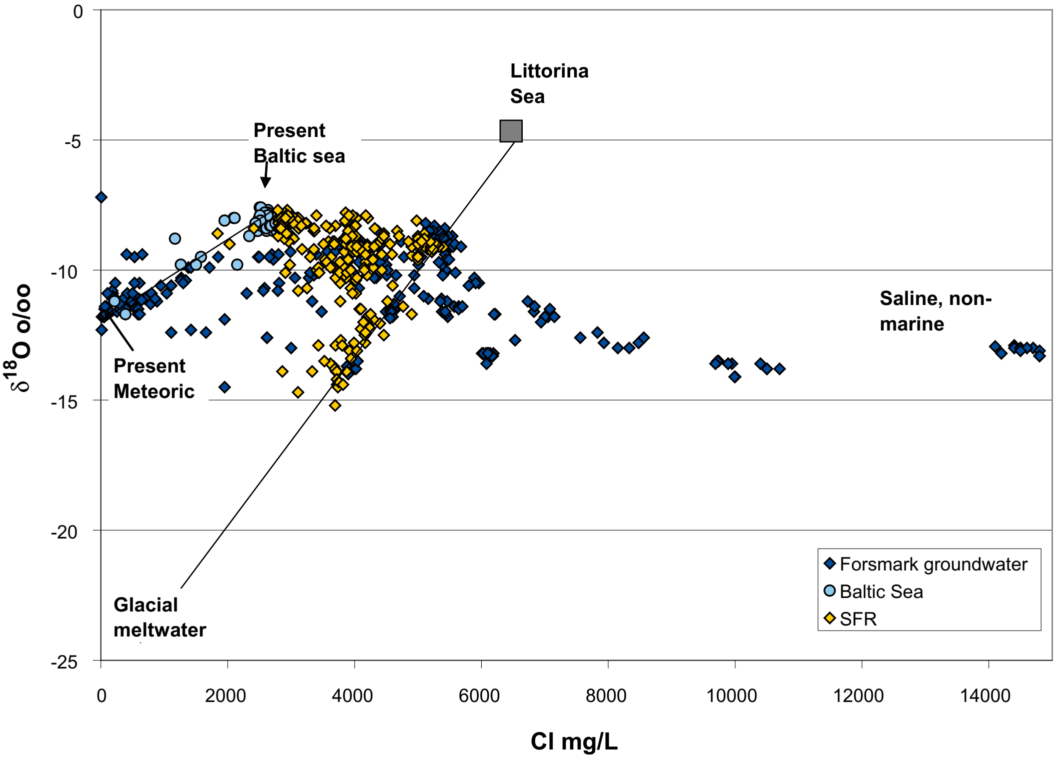


***Figure 5-39.** δ^{18}O versus Cl for Forsmark groundwaters, Baltic Sea and samples close to the SFR facility adjacent to the Forsmark candidate area. Note that the labelled groundwater types represent assumed end members apart from the brackish to saline non-marine groundwaters.*

no groundwater with this composition is found in the bedrock. Instead, a number of samples plotting along a mixing line between the estimated Littorina composition and a much diluted and depleted $\delta^{18}O$ groundwater can be outlined. Most of these waters obviously have chloride contents significantly higher than today's Baltic Sea. Thus, the question is whether these waters have a convincing marine origin or not. A number of indicators can be applied to establish the marine origin of a groundwater, for example, the contents of magnesium, sulphate and bromide/chloride ratios.

However, none of these parameters are entirely conservative but are modified due to different reactions. Generally, it is acknowledged that the Br/Cl ratios are relatively stable compared with sulphate which can decrease (accompanied by an increase in bicarbonate) due to microbial reactions. In addition, water-rock interaction (including ion exchange) will influence the Mg, K, Ca and Na proportions relatively fast compared to the Br/Cl ratios.

From Figure 5-40 it can be concluded that groundwaters with approximately marine Br/Cl ratios show a large variability in their $\delta^{18}O$ values, supporting a dilution of the Littorina water mainly with a glacial meltwater as indicated in Figure 5-41.

Figures 5-41 and 5-42 show Br/Cl ratios versus magnesium and sulphate. It is evident from these plots that the brackish marine waters in the bedrock are influenced by reactions, indicated by the large variations in Mg and SO_4 values in groundwater samples with similar Cl contents (Figure 5-43). None of the samples with higher salinities than the present Baltic Sea have maintained their marine SO_4/Cl or Mg/Cl ratios /cf. Tröjbom et al. 2007/.

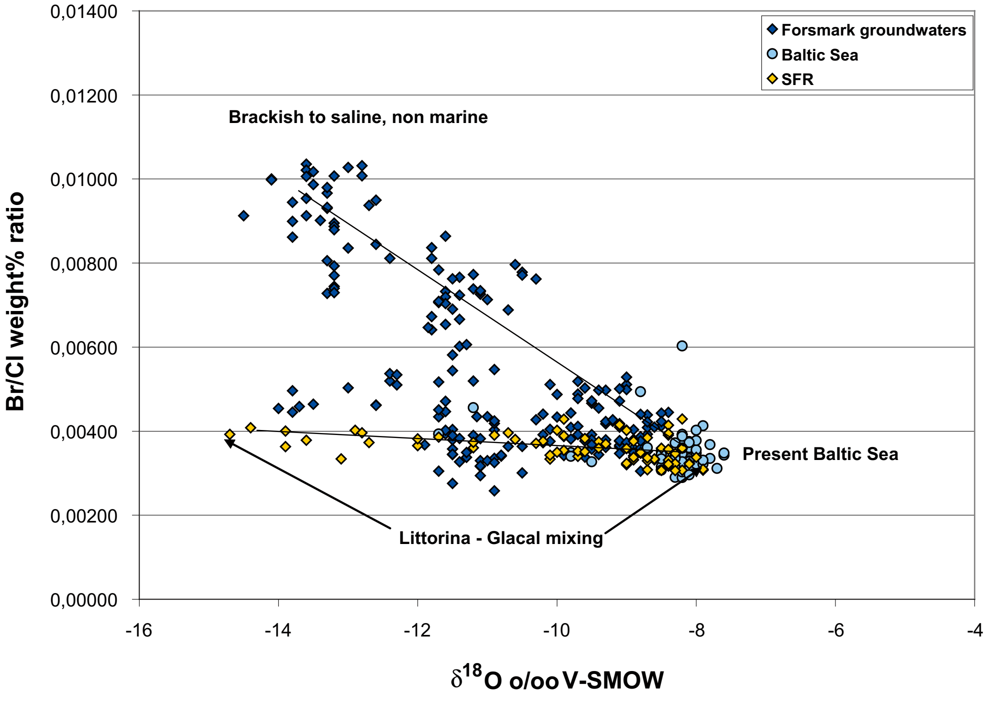


Figure 5-40. Br/Cl weight ratio versus $\delta^{18}O$‰ V-SMOW for Forsmark groundwaters, Baltic Sea and samples from close to the SFR facility adjacent to the Forsmark candidate area. Note that the labelled groundwater types represent assumed end members apart from the brackish to saline non-marine groundwaters.

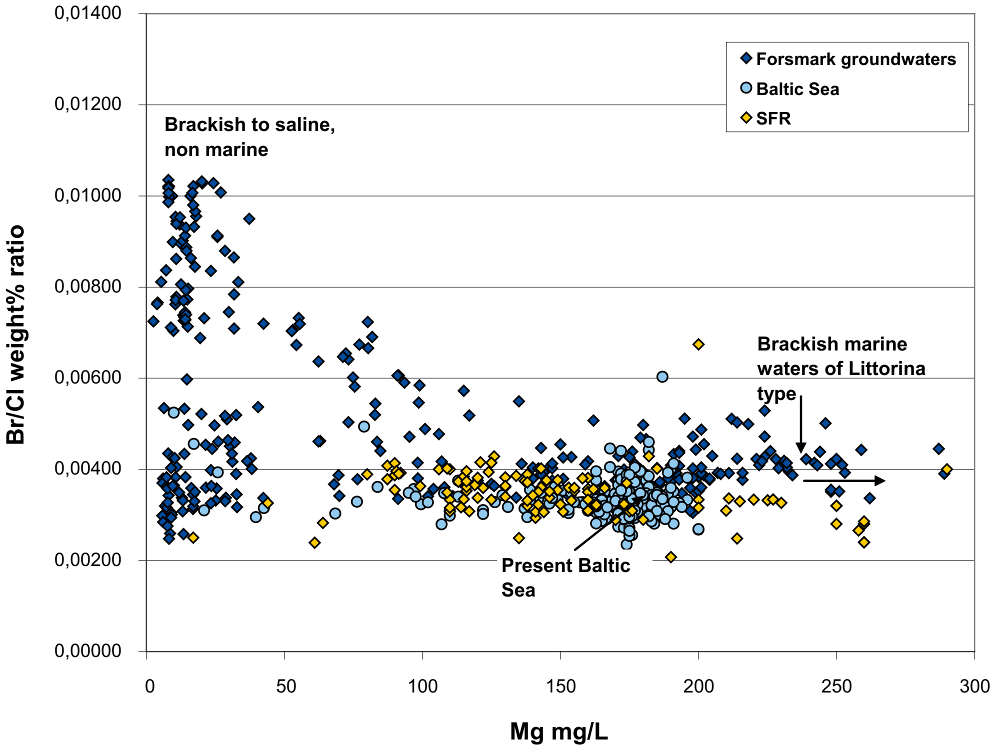


***Figure 5-41.** Br/Cl weight ratio versus Mg contents for Forsmark groundwaters, Baltic Sea and samples from the SFR facility adjacent to the Forsmark candidate area Note that the labelled groundwater types represent assumed end members apart from the brackish to saline non-marine groundwaters.*

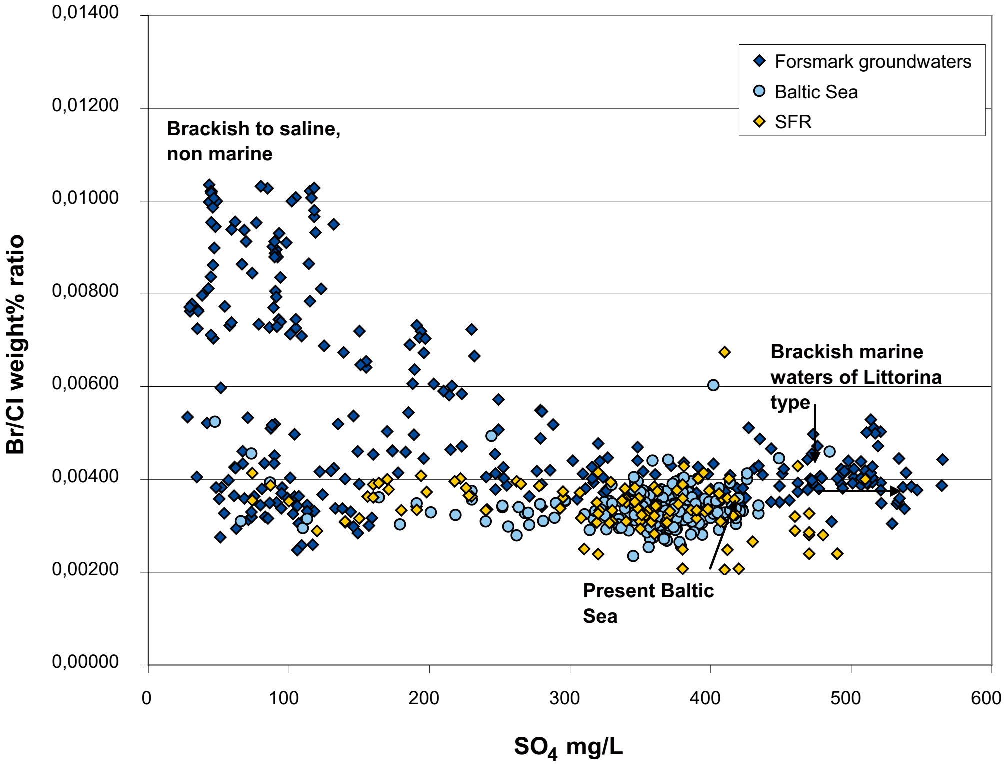


***Figure 5-42.** Br/Cl weight ratio versus Mg contents for Forsmark groundwaters, Baltic Sea and samples from the SFR facility adjacent to the Forsmark candidate site. Note that the labelled groundwater types represent assumed end members apart from the brackish to saline non-marine groundwaters.*

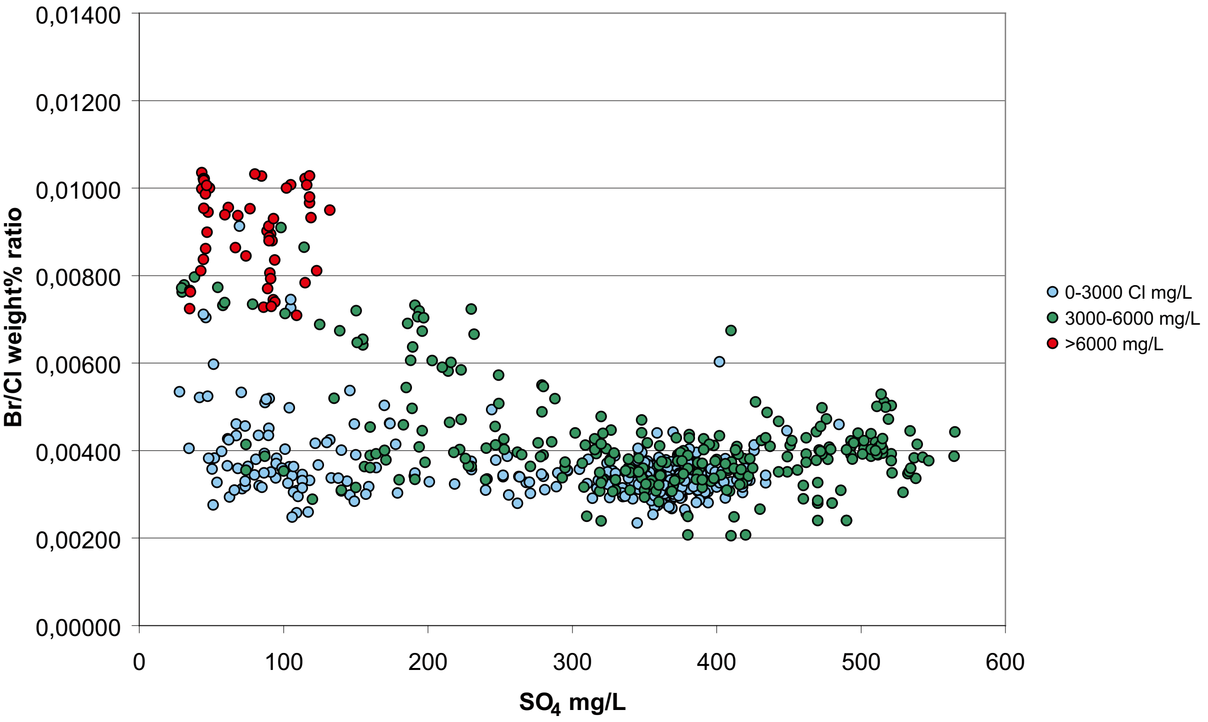


Figure 5-43. *Br/Cl weight ratio versus sulphate contents for Forsmark groundwaters, Baltic Sa and samples from the SFR facility adjacent to the Forsmark candidate area divided into different Cl contents.*

In conclusion:

- Despite that the bedrock groundwaters are influenced and modified by organic and inorganic reactions, there is an overall good correlation between indicators such as magnesium, potassium, sodium and sulphate, in addition to Br/Cl ratios, supporting a marine origin for some of the Forsmark groundwaters.
- The $\delta^{18}O$ signature in these waters shows a large spread and a mixing trend between brackish marine water of Littorina type and glacial meltwater. Dilution of the Littorina Sea water with a glacial meltwater explains the comparably low $\delta^{18}O$ values in groundwaters with a relatively high Cl contents.
- There is strong evidence of mixing between these brackish marine waters + glacial meltwater with a deeper, brackish to saline non-marine water. This mixing may be much enhanced by the drilling and sampling so that its extent during undisturbed conditions is difficult to judge.
- The fact that the brackish-marine Littorina type waters have been influenced by both mixing and reactions explains partly the underestimation of the Littorina component in the mixing proportion calculations (M3) /Gurban 2008/.

5.9 Origin and evolution of deeper saline groundwaters

5.9.1 Background

This chapter is an updated and modified version of that already outlined in /L.2.1 Chapter 14 in SKB 2006a/. A comprehensive study to the origin and evolution of the deep highly saline groundwaters at Forsmark goes beyond the scope and resources of the hydrogeochemical programme, but considerable insight is obtained as a natural byproduct from the many areas of study conducted to provide input to the final Forsmark Hydrogeochemistry Site Description Model.

Groundwaters of high salinity are ubiquitous at depth in the Fennoscandian Shield and, as such, their origin and evolution form an integral part of the hydrogeochemical site characterisation investigations. At the Swedish and Finnish sites characterised within the respective radwaste programmes, true brines (> 100 g/L TDS) are almost certainly present but have not been sampled due to limitations of the drilling programmes. Their influence as a brine component is to varying degrees indicated close to repository depths under present-day undisturbed bedrock conditions through mixing process by upward molecular diffusion. Mixing to higher bedrock levels may also result under disturbed conditions, for example, during glacial events where permafrost may be accompanied by an upward migration of older, deeper saline groundwaters to shallower levels (cf. section 4.7). Alternative sources of highly saline mixing at repository levels may be traced back to the formation and downward propagation of near-surface 'freeze-out' brines in association with permafrost conditions /Boulton et al. 2001/. Furthermore, during the repository construction and operational phases, upconing of deep saline groundwaters is predicted to occur and on occasions this has been observed at the borehole scale at the Laxemar-Simpevarp and Forsmark sites. The main consequences of highly saline groundwater incursions at repository levels include: a) a potential source of sulphate which, through microbial activity (i.e. sulphate reducing bacteria), may produce sulphide that can promote canister corrosion, and b) the gradual deterioration of the physico-chemical properties of bentonite buffer material due to increased salinity.

To characterise these saline end members it is therefore important to understand fully the past and present (and potentially predict the future) hydrochemical evolution of the candidate site in question, and to use such information to help assess potential repercussions on long-term repository safety and performance.

5.9.2 Deep brines and origin of salts

The Swedish context

Based on available deep groundwater data from the Swedish Precambrian basement /Juhlin et al. 1998/, Figure 5-44 provides a schematic illustration of a vertical transect across Sweden along the direction of the regional hydraulic gradient. Meteoric recharge is initiated in the central Palaeozoic Caledonides to the west and deep discharge is expected along the eastern coastline to the southeast; in this case the coastal section has been constructed to include the Simpevarp area site investigation localities, but equally well reflects the coastal situation at the Forsmark site. The effect of the meteoric water recharge can be detected to depths approaching 5 km as indicated from the deep Gravberg borehole at Siljan, and to a lesser projected depth at the Stripa site (2–3 km) which lies within a major discharge area. From Zinkgruvan to the eastern coast, i.e. representing a distance of approxímately 230 km, the generally low topography is characterised by more localised recharge/discharge systems extending to various depths but probably averaging out around 1,000 m; in this region deep, highly saline groundwaters (and possibly brines) are correspondingly close to the surface. At the site characterisation localities at Laxemar-Simpevarp and Forsmark it is therefore expected that these groundwaters are present at relatively shallow depths (1,000–2,000 m).

Measured salinities

Brine is normally defined as a fluid comprising greater than 100 g/L TDS. In the Swedish basement at depths mostly around 1,000 m this compares with maximum values of 80 g/L TDS for the most saline groundwater at the Laxemar subarea (KLX02), 40 g/L TDS at the encapsulationplant in Oskarshamn (KOV01), 29 g/L TDS at the Simpevarp peninsula (KSH03A), 20 g/L TDS at the Ävrö island (KAV04A), 21 g/L TDS at the Äspö island (KAS03) and 25 g/L TDS at the Forsmark site (KFM09A). With the exception of the Ävrö island (Ca/Na = 0.88), all these deep groundwaters are Ca-Na-Cl in type with the Ca/Na ratio ranging from 1.06 at

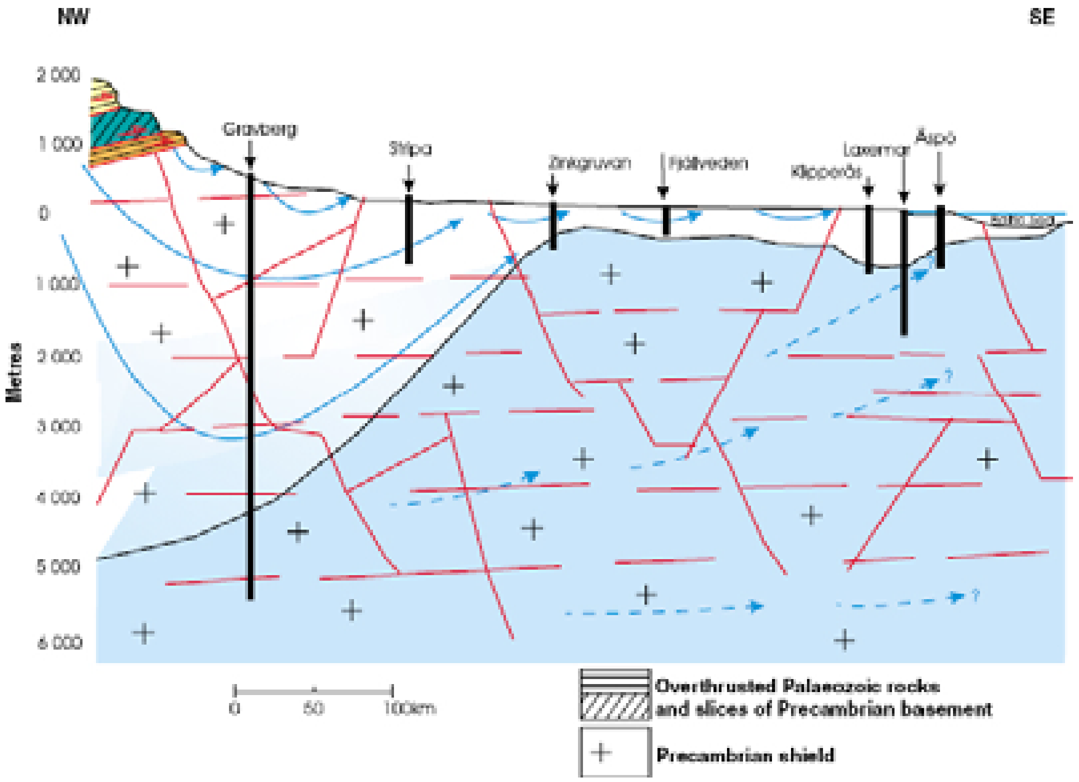


***Figure 5-44.** Schematic NW-SE transect from the western Caledonides to the SE coast showing the major regional recharge/discharge areas and the approximate depths of the highly saline groundwaters (light blue) and brines (darker blue colour) /after Juhlin et al. 1998/.*

the Simpevarp peninsula, to 2.12 at the Forsmark site, to 2.34 at the Laxemar subarea. In the Finnish basement maximum salinity levels around the 1,000 m depth are within a similar range, for example 70 g/L TDS at Olkiluoto (KR4 861; /Pitkänen et al. 1999/) and 44–48 g/L TDS at the Kotalahti Mine /Blomqvist et al. 1989/. Increased calcium with depth in granitic domains normally results from increased albitisation of plagioclase and hornblende when in contact with sodium-rich groundwaters. Under long time periods these processes will result in the removal of sodium from solution and release calcium to the groundwaters.

To illustrate further the transition depth to a marked increase in salinity, Figure 5-45 plots chlorinity with depth for selected Fennoscandian sites. Comparison shows that the transition point to a more highly saline environment (10,000–15,000 mg/L Cl) is site dependent, with the Laxemar-Simpevarp and Forsmark sites indicating depths at approximately 700–1,000 m. In contrast, Olkiluoto and Oskarshamn show this transition at shallower depths (at 500–600 m).

In the Canadian Shield area reported salinities in crystalline rock environments are considerably more concentrated than those so far measured in Sweden and Finland. Furthermore, decreasing flow to stagnant groundwater conditions are commonly established at relatively shallow depths (at around 300 m) irrespective of variations of local topography, distribution of recharge/discharge zones and rock types, and consequently salinities increase rapidly /Gascoyne et al. 1987/. Measured maximum Ca-Na-Cl brine compositions from some deep mine sources at around 1,500–1,650 m (e.g. Sudbury, Ontario, Thompson, Manitoba and Yellowknife, North West Territories) range from 254–325 g/L TDS with Ca/Na ratios of 1.8 at Yellowknife, 1.4 at Thompson and 2.8 at Sudbury /Frape et al. 1984/.

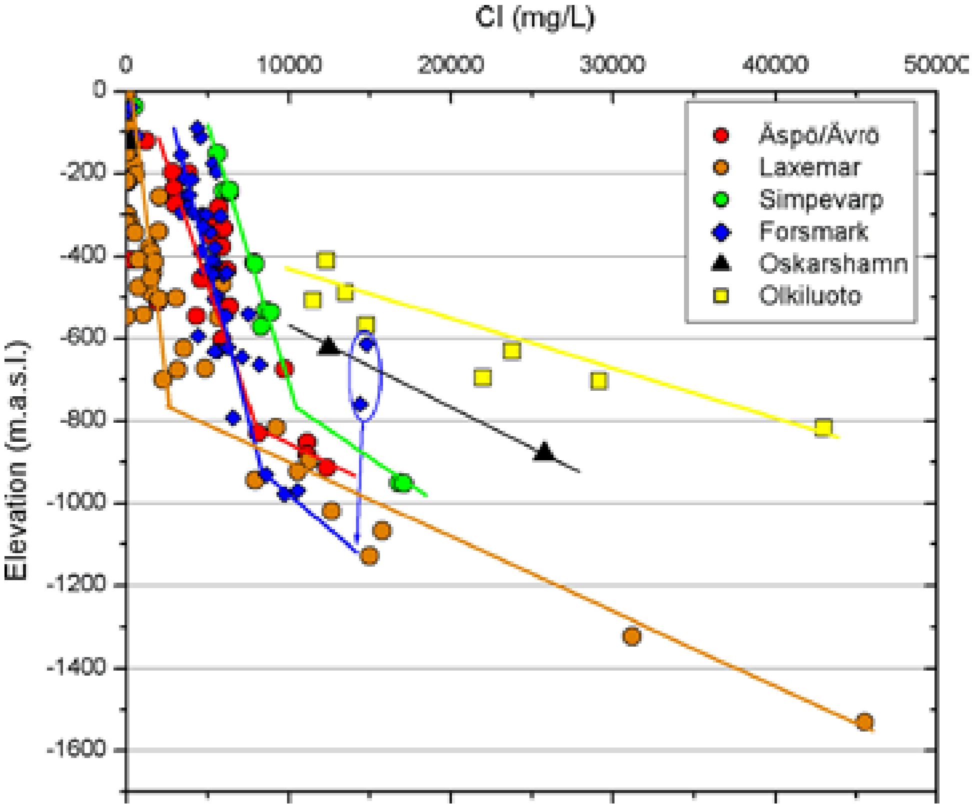


***Figure 5-45.** Depth comparison of chlorinity (categories 1–4) at selected Fennoscandian sites. (Note the most saline Forsmark samples (ringed) have been subject to upconing and should plot at greater depths as shown).*

Sources of salinity

As summarised by /Lampén 1992/, there are several potential sources to the salinity measured in deep groundwaters:

- *Allochthonous sources* such as: a) ancient Proterozoic (older than 570 Ma) seawater or basinal brines, b) Palaeozoic (older than 250 Ma) basinal brines, c) seawater and evaporites, and d) young Holocene (10–0 ka) brackish waters.
- *Autochthonous sources* such as: a) residual metamorphic/igneous fluids, b) hydrolysis of silicate minerals, and c) dissolution/leaching of salts present interstitially in the rock matrix.

Under disturbed conditions, for example, in the Fennoscandian Shield where crustal stress release is a on-going process responding to glacial isostatic recovery, an additional source may derive from the rupture and/or dissolution of fluid inclusions (which may be allochtonous or authochtonous in origin) located in and/or around some of the major rock-forming minerals (mostly quartz). Furthermore, periodic permafrost conditions related to glacial events may produce a freeze-out brine component of uncertain importance (cf. section 5.7).

It is generally accepted that no one process or source can account for the observed salinities in the basement Shield areas of Canada and Fennoscandia and most reported occurrences seem to represent mixtures of meteoric water with a highly concentrated brine. From the many studies carried out in Canada the brine component initially was attributed a 'rock heritage' origin based on water-rock interaction processes over long periods of geological time /Frape and Fritz 1987/; this was largely supported by /Gascoyne et al. 1987/ with the additional suggestion that a component of ancient sedimentary basinal brines of marine origin may also have been involved /Gascoyne et al. 1989/. Later /Bottomley et al. 1994, 1999, 2002/ have argued for a primarily marine origin to the Canadian brines and more recently /Starinsky and Katz 2003/ have strongly supported an origin based on freeze-out processes from seawater during glacial events

In Fennoscandia the available data on basement brines and their origin is sparse in comparison with Canada; this is partly due to the absence of extreme brines associated with the Fennoscandian crystalline basement, at least to the levels so far sampled and studied. In general the origin of the salinity is unclear; much of the evidence would appear to support a non-marine sources such as residual metamorphic/igneous fluids and fluid inclusions /Nordstrom et al. 1989/ accompanied by intensive meteoric water-rock interactions. The problem with these interactions is that they may mask any possibility of addressing whether non-marine/old marine mixing has occurred at some period of time in the distant past. A marine origin for the brine salinity has been invoked by /Fontes et al. 1989/ and suggested also by /Louvat et al. 1999/ and /Casanova et al. 2005/. As a further complication, selected Fennoscandian highly saline waters (i.e. from Äspö, Olkiluoto and Hästholmen) have become highlighted recently as support for the freeze-out origin hypothesis /Starinsky and Katz 2003/.

5.9.3 The Fennoscandian saline to highly saline groundwaters

To date no groundwaters of truly brine character (i.e. > 100 g/L TDS) have been sampled from the SKB site characterisation investigations. In all probability this is because of the limited depth of the drilling campaign as indicated by the greatest salinity associated with deepest drilled borehole at Laxemar subarea (KLX02: 1,705 m). Based on the discussion in section 1.2.1, a further 500–1,000 m of drilling most likely would have intercepted brine-type waters. The characterised deep groundwaters to around 1,000 m from the various sites are therefore mixtures of younger waters of different origin with variable amounts of deep, ancient brine waters. The antiquity of the brine component (> 1.5 Ma) is suggested from ^{36}Cl dating of brackish-saline non-marine to highly saline groundwaters collected at different depths from the Äspö island /Louvat et al. 1999/ and from the Laxemar-Simpevarp and Forsmark sites (cf. section 5.9).

Of the studied sites under discussion, perhaps those most likely to contain a deep brine component are: a) the deepest drillings (i.e. Laxemar subarea), b) areas of potential 'regional' discharge (e.g. Simpevarp peninsula), and c) areas to some extent shielded from recharging waters (e.g. Forsmark).

Unravelling the contrasting palaeo-origins of the salinity may still be possible by careful interpretation of chemical and isotopic indicators not only in the groundwaters, but also associated with fracture filling materials from ancient, and continuously reactivated water-conducting fracture systems.

Chemical and isotopic indicators

To trace the origin and palaeoevolution of highly saline brines requires a coordinated and collective use of chemical and isotopic indicators. The following list of indicators reported in the literature has been used with varying success at different sites:

- ^{36}Cl age-dating (up to at least 1.5 Ma),
- Ca/Na ratio > 1 (majority of Canadian basement brines and Fennoscandian highly saline groundwaters),
- high/low Br/Cl ratio (indicates a non-marine/marine origin respectively),
- high/low Li/Br ratio (indicates a non-marine/marine origin respectively),
- high radiogenic ^{87}Sr/^{86}Sr ratio (long residence time water/rock interaction processes),
- high/low positive ^{37}Cl/^{35}Cl ratio (indicates a non-marine/marine origin respectively),
- heavy δ^{18}O and δD values (suggests long residence time water/rock interaction processes),
- high concentrations of dissolved gases of deep origin (N_2-$CH_4 \pm H_2 \pm 3He$) with heavy δ^{13}C values and the presence of ^{3}He indicating a deep mantle origin,
- anomalous anaerobic microbial populations from depth.

Major and trace ions

A standard diagram that provides some initial understanding to the groundwater system is to plot bromide against chloride (considered to be the two most conservative tracers) and to compare the outcome with the seawater dilution line which has a constant Br/Cl weight ratio of 288 (Figure 5-46). First impressions indicate that the groundwaters do not have a marine origin since they do not plot on or close to the seawater dilution line; the bromide relative to the chloride is too concentrated and suggests therefore an alternative source(s) of salinity. Enriched bromide may be explained by long term water-rock reactions in magmatic (and metamorphic) rocks which normally contain much more bromide than seawater (e.g. in fluid inclusions, along mineral grain boundaries, in crystal lattices etc) giving Cl/Br weight ratios of around 100 or less /Stober and Bucher 1999/. Bromide enrichment can, however, result also from sea water evaporation processes, for example, when a TDS value of around 100 g/L is achieved through evaporation, halite (NaCl) crystals begin to form thus removing chloride from the evaporating seawater, and thereby enriching bromide in the residual seawater.

Assuming for the moment that the bromide enrichment has resulted from water-rock interaction, what other supporting evidence is there? Granite and granodiorite comprise the main rock types within the Forsmark target area. The major rock-forming minerals susceptible to groundwater reaction and alteration are K-feldspar, plagioclase, quartz and micas (biotite/muscovite), giving rise respectively to the redistribution and potential concentration in the rock matrix porewaters and fracture groundwaters of, for example, commonly Na, K, Ca, Rb, Ba, Sr and Fe. With decreasing flow to stagnant groundwater conditions at depth, accompanied by greater water/rock interaction, these constituents should also increase in concentration accordingly.

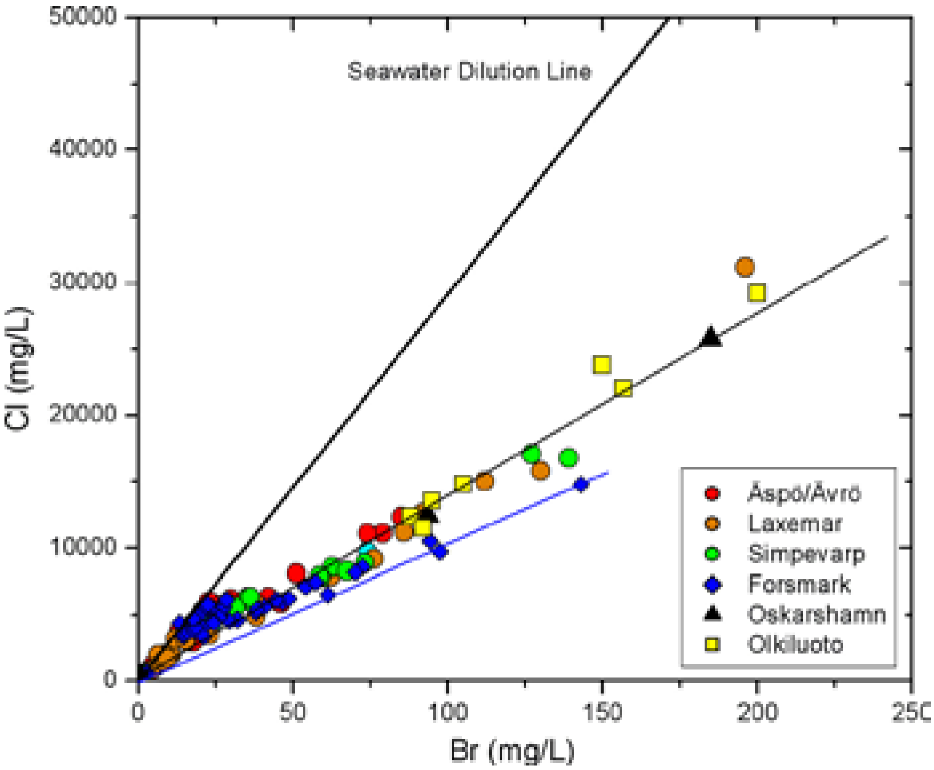


***Figure 5-46.** Plot of chloride against bromide (categories 1-4) for selected Fennoscandian sites showing close correlation; there is a clear deviation from the seawater dilution line.*

Figure 5-47 which plots calcium against sodium shows clearly in all groundwaters a transition from a Na-Ca-Cl to a Ca-Na-Cl type groundwater, and the depth of transition is site dependent. In most cases (e.g. Forsmark area, Simpevarp subarea, Olkiluoto) this reflects the quite rapid transition from the younger, generally more sodium-rich brackish marine (Littorina) groundwater, to an older, calcium-rich non-marine brackish groundwater. Calcium then continues to increase gradually and systematically with depth as these brackish non-marine groundwaters evolve to saline and then highly saline varieties. These trends are particularly well illustrated in the Forsmark area (cf. section 5.10.2). In other cases (e.g. Laxemar subarea, Äspö, Oskarshamn) where there is only sporadic influence from the Littorina component, the observed Na-Ca-Cl transition to Ca-Na-Cl groundwaters is less rapid being controlled more by local hydraulic conditions.

In some cases, particularly Forsmark, the increased salinity gradient with depth devoid of Littorina influence can be attributed to processes which have occurred prior to the incursion of the Littorina Sea waters. For example, mixing and dilution of the brine component with lower saline groundwaters at shallower, slightly transmissive depths reflects advection, whilst at decreasing flow to stagnant groundwater conditions at depth, mixing is driven by upward molecular diffusion. Nevertheless, under both conditions it is the same deep brine component that is being modified.

Strontium shows a strong positive correlation with calcium, which is not unexpected because of their geochemical similarity, indicating a common genesis to the brine component in the saline to highly saline groundwaters. Plotted against bromide (Figure 5-48) strontium shows less enrichment (relative to bromide) for all groundwater types, although this is quite variable with the Forsmark (and Olkiluoto) groundwaters showing least enrichment with increasing depth. In contrast, the Laxemar-Simpevarp and Oskarshamn groundwaters appear to show more enrichment relative to bromide with depth, with the deepest Laxemar groundwaters indicating most enrichment.

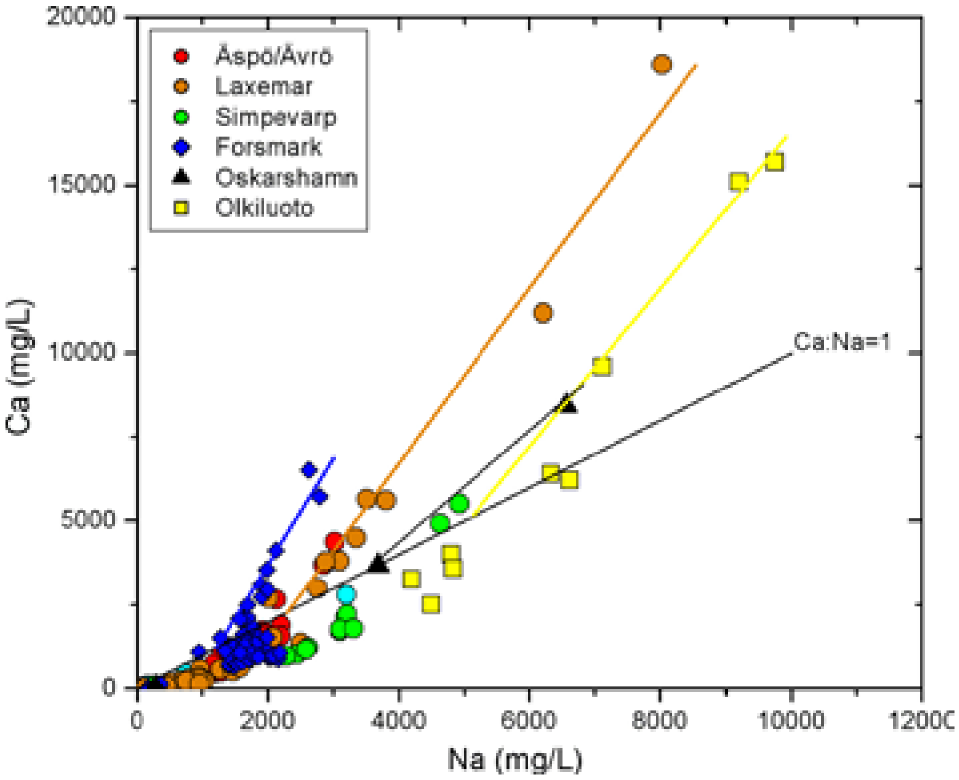


***Figure 5-47.** Plot of calcium against sodium (categories 1–4) showing for all groundwaters a shift from Na-Ca-Cl to Ca-Na-Cl type with increasing depth and salinity.*

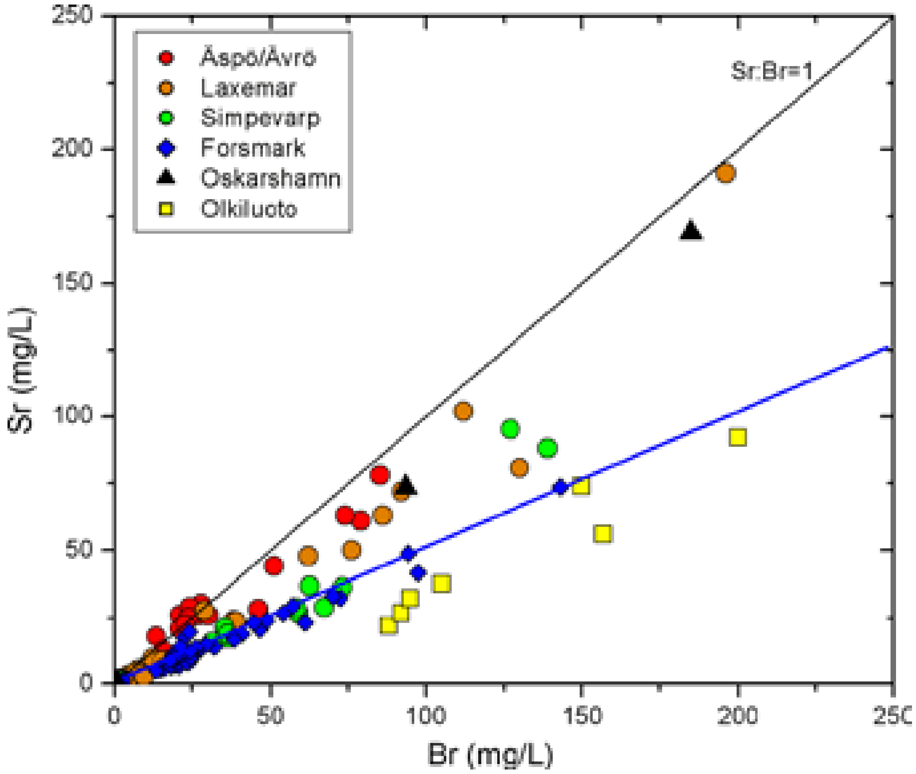


***Figure 5-48.** Plot of strontium against bromide (categories 1–4) showing varying strontium enrichments for the different groundwaters with increasing depth.*

Strontium isotope ratios ($^{87}Sr/^{86}Sr$) from the Forsmark groundwaters have been discussed in section 5.10.2 showing the system to be very heterogeneous and many types of water-rock processes have contributed to this state. At this locality at least, the strontium isotopes do not differentiate an increasing trend of water-rock interaction with depth, but rather at all levels within the bedrock.

High sulphate can be yet another indicator of increasing water-rock interaction processes with depth. Figure 5-49 shows notable differences between the various sites based on sulphate content; the Oskarshamn and Olkiluoto sites are characterised by very low sulphate and Forsmark, at shallow depths dominated by high sulphate from the brackish marine (Littorina) groundwaters, shows a trend to low sulphate at increasing depth from around 700 m downwards, i.e. now dominated by brackish to saline non-marine groundwaters. These observations of decreased sulphate may be the result of site-specific reducing conditions involving microbial activity (i.e. sulphate-reducing bacteria) in the presence of suitable reductants such as methane gas (e.g. Olkiluoto and Oskarshamn and maybe Forsmark; cf. section 5.5). However, it is also possible that the lack of gypsum in the fracture fillings contributes also to the situation.

In contrast, the Äspö/Ävrö/Laxemar-Simpevarp group show in common an increase in sulphate with depth. They also show, in particular at Laxemar, a levelling of sulphate at around 600–900 mg/L (at 900–1,000 m depth) despite a significant increase in salinity from 15,000–50,000 mg/L Cl. This limitation of sulphate content in deep saline groundwaters was also noted by /Gascoyne 2004/ at the URL site in Canada; in this case it was attributed it to the solubility control exerted by gypsum which was close to saturation in the groundwaters. This explanation is probably valid for the Swedish groundwaters although the presence of fracture gypsum has only been observed at Laxemar and even then in very small amounts (cf. section 5.5). However, it is a fact that the only systems with high sulphate contents are Laxemar-Simpevarp and the Canadian Shield systems where the occurrence of gypsum in the fracture fillings has been identified.

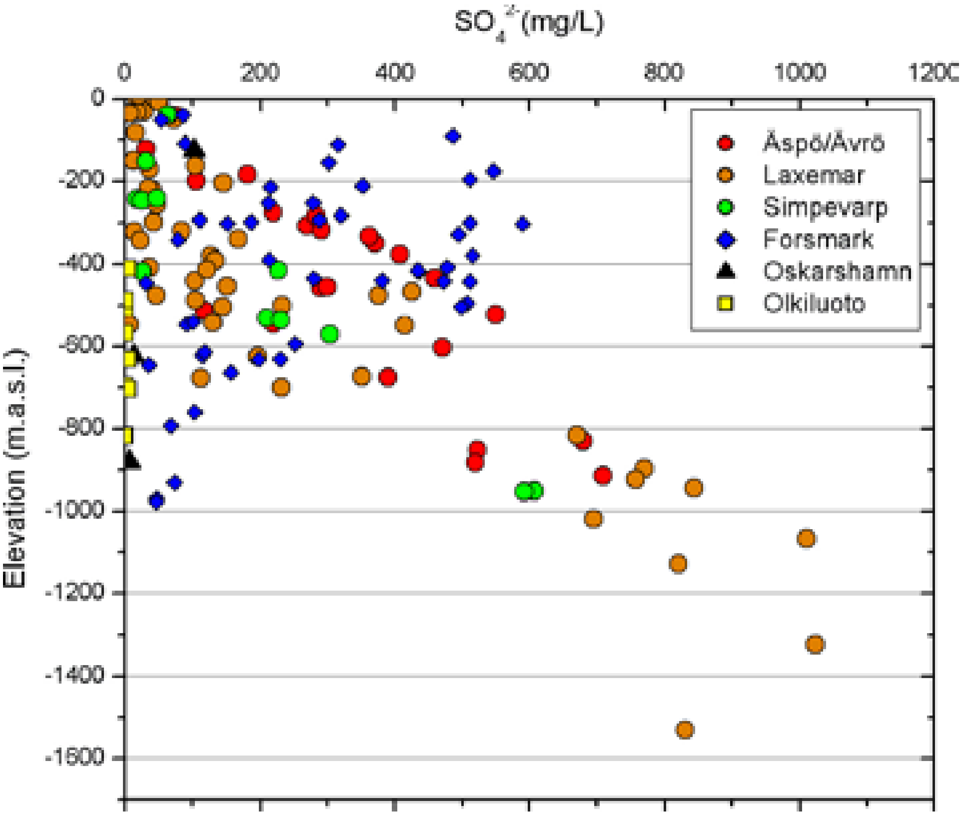


Figure 5-49. *Plot of SO_4 versus elevation (categories 1–4).*

Figure 5-50 showing the distribution of caesium exemplifies suggested increases in concentration related to depth for several of the trace elements, although in cases there are inadequate data, especially at depth. The sharp increase at around 1,000 m for the Laxemar groundwaters (and probably also Simpevarp and Oskarshamn) is again noticeable, representing the transition to decreasing flow to stagnant conditions. This transition occurs at much shallower depths at Forsmark, i.e. at around 600–700 m marked by the decrease in caesium. (Note that contamination from hydraulic tracer tests may have contributed to some of the high values (cf. section 4.1.17).

By plotting Ca/Mg versus Br/Cl, Figure 5-51 provides an opportunity to interpret further the complex nature of Swedish basement groundwaters, particularly at depths < 1,000 m. The figure clearly shows the Baltic Sea group of modern marine waters and also the deepest and oldest non-marine (or non-marine/old marine mixing origin) saline groundwaters from the Laxemar, Oskarshamn and Forsmark sites. Between these two extreme end members are located most of the fresh, brackish, and brackish to saline groundwater data from all the sites. Circled in green are most of the brackish marine groundwaters, many with a weak to strong Littorina Sea component. The red and turquoise double arrows show two potential evolution pathways towards the deep, highly saline non-marine groundwater types. Much of the data along these pathways (i.e. to depths of around 1,000 m) represent groundwaters which contain an increasing component of the highly saline non-marine or non-marine/old marine mixing end member. Interestingly, Laxemar and Forsmark appear to show a difference in evolution pathways (also noted in several of the other plots) which led to the recommendation some time ago that the Laxemar highly saline end member should not be used in groundwater mixing calculations in the Forsmark area.

Figure 5-51 can be used also to achieve some perspective of the Fennoscandian deep groundwaters in relation to three well characterised Canadian brine occurrences located at Sudbury, Yellowknife and Thompson from /Frape et al. 1984/. The main Laxemar (+ Olkiluoto, Simpevarp and maybe Oskarshamn) evolution pathway coincides clearly with the Sudbury site. This is true also for Forsmark although there may be a small deviation towards the Yellowknife

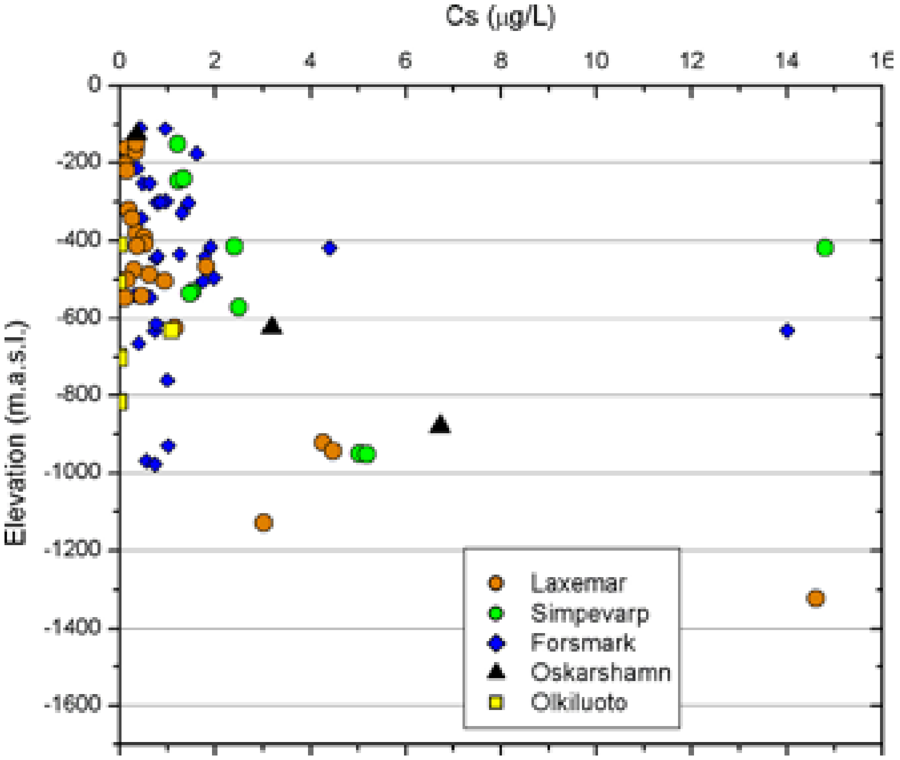


Figure 5-50. *Plot of caesium versus depth (categories 1–4) for the different sites (no data available for Äspö/Ävrö or Olkiluoto).*

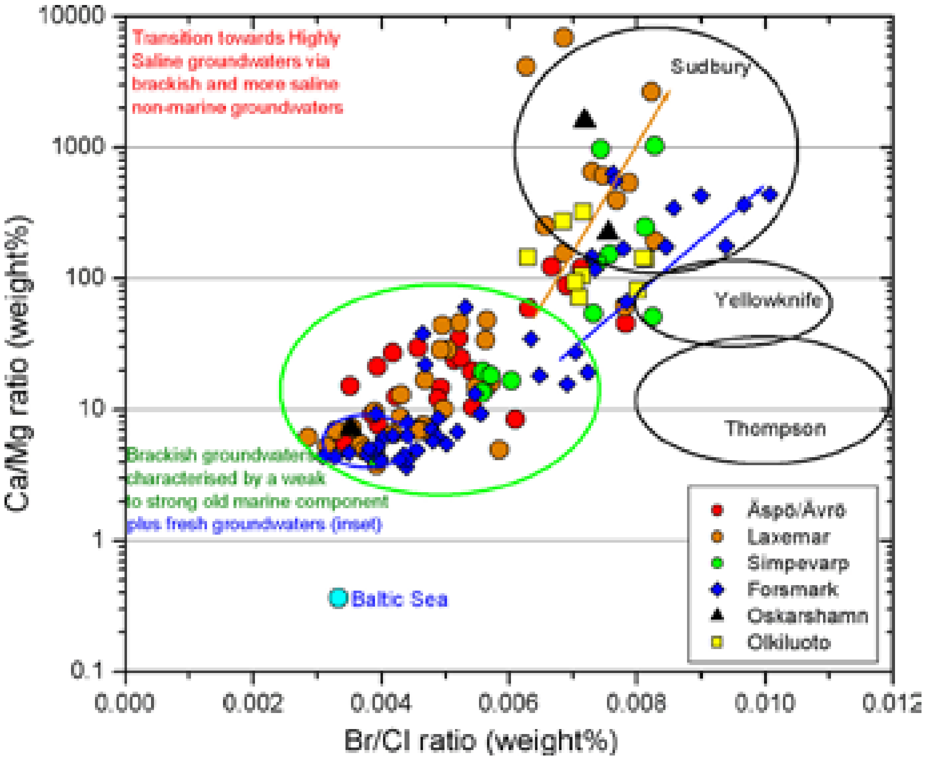


Figure 5-51. *Plot of Br/Cl versus Ca/Mg (weight%) (categories 1–4) showing the major evolution trends with increasing depth for selected Fennoscandian sites. Orange and blue arrow directions indicate an increasingly deep highly saline component in the Fennoscandian groundwaters. These sites are also compared to three Canadian localities characterised by deep brines /after Frape et al. 1984/.*

site. In addition, the Ca/Na ratios for the Laxemar and Forsmark groundwaters coincide more closely with the Sudbury site. Care, however, should be taken not to interpret too much from these observations; the main point is that these selected deep Fennoscandian groundwaters show an increasing brine component with depth which corresponds to some Canadian brine localities, and that the Forsmark groundwaters suggest a different evolution pathway from that indicated by the Laxemar-Simpevarp group of groundwaters.

To pursue the nature of the Fennoscandian brine component, lithium enrichment has been shown to be a common feature in many brines of different origin (e.g. oilfields, sedimentary basins, crystalline Shield areas) and is normally expressed as a Li/Cl ratio, which frequently exceeds that of modern seawater /Chan et al. 2002/. These ratios, together with the isotopes of lithium, ^{6}Li and ^{7}Li, have been applied recently to the Yellowknife brines to show a possible marine source /Bottomley et al. 1999/. Such isotope analyses, however, are expensive and time-consuming and were not prioritised for the Swedish programme. Nevertheless, the use of lithium and chloride has been applied as an additional tool to indicate water-rock interaction processes that may have contributed to the salinity of the deep Ca-Na-Cl groundwaters at Forsmark and the other Fennoscandian sites.

Figure 5-52 shows a plot of lithium versus bromide. This is identical to a plot of lithium against chloride. Of interest to note is: a) only the Forsmark brackish marine groundwaters plot along the seawater dilution line even though similar types of groundwaters exist at Simpevarp and to a lesser extent at Äspö/Ävrö (similar groundwaters from Olkiluoto may also fall into this category but there is a lack of available data), b) the Forsmark, Oskarshamn and Olkiluoto groundwaters show a depletion of lithium relative to bromide, and c) the Laxemar-Simpevarp group groundwaters all show an enrichment of lithium relative to bromide. This suggests that the Laxemar-Simpevarp group are more characterised by water-rock interaction processes when compared to Forsmark (and probably Olkiluoto). These patterns, however, may be a reflection of available bedrock lithium at the different sites; apparently there are no lithium data from the different rock types representing each of the sites to determine any lithological influence. It may be significant, however, that both Forsmark and Olkiluoto show similar trends when the respective rock types are so different geochemically.

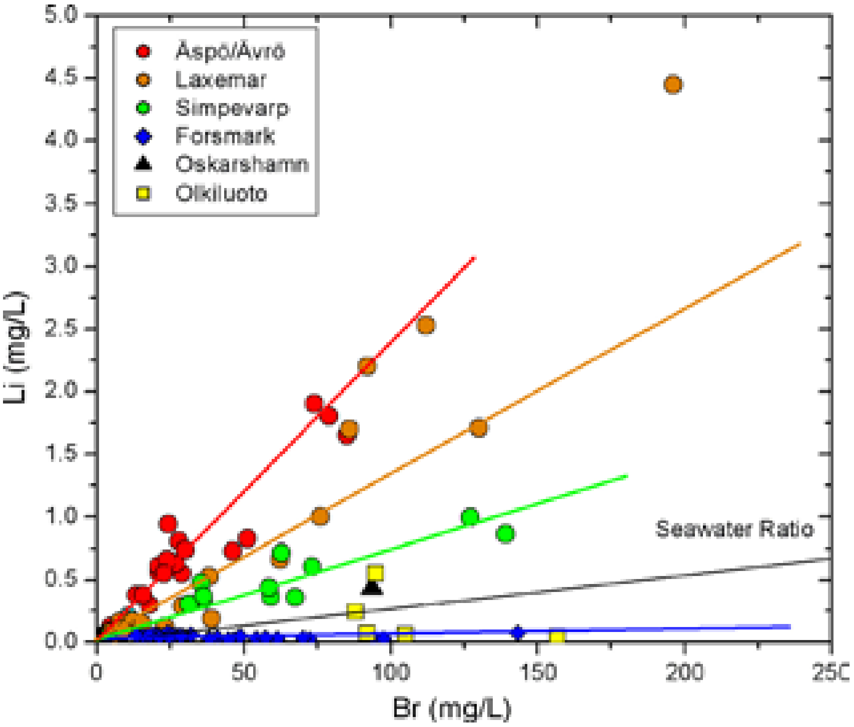


Figure 5-52. *Plot of lithium versus bromide (categories 1-4) for the different sites related to the seawater concentration line.*

To improve the resolution of the low lithium Forsmark groundwaters, a similar plot of only the Forsmark site is shown in Figure 5-53. The plot differentiates the shallow (0–600 m), younger marine system (Littorina/Baltic) from the deeper (600–1,000 m), older brackish to saline non-marine system. The latter shows no significant lithium increase (relative to bromide enrichment) with depth; however the deepest sample from KFM09A shows some enrichment but still well below the Laxemar-Simpevarp values (cf. Figure 5-52).

Stable isotopes

Stable chlorine isotopes may be used also as an indicator of marine versus non-marine derived groundwaters and therefore further support for detecting a transition towards non-marine deeper saline groundwaters. According to /Frape et al. 1996/ modern Baltic and possibly palaeo-Baltic waters may be recognised by negative δ^{37}Cl signatures related to salt leachates from Palaeozoic salt deposits south of the Baltic Sea. Influence by water-rock interaction (i.e. characteristic of some deep, highly saline groundwaters and brines) tends to result in positive δ^{37}Cl signatures. /Clark and Fritz 1997/ also show a clear distinction between the Fennoscandian and Canadian Shield crystalline rock groundwaters and groundwaters from sedimentary aquifers.

Taking into consideration the analytical uncertainty of around ±0.2‰ SMOC, Figure 5-54 shows that non-marine derived groundwaters significantly enriched in Br (i.e. Laxemar-Simpevarp), compared to low Br marine waters (i.e. Baltic Sea) and those groundwaters with a clear marine signature (i.e. Forsmark), display positive δ^{37}Cl values and can be interpreted as a water-rock interaction signal; this is in accordance with discussions above (e.g. Figure 5-52). In contrast, the Forsmark groundwaters are characterised by more marine-derived Br/Cl ratios clustering close to 0‰ SMOC. With increasingly enriched bromide there is a trend to more positive δ^{37}Cl values (> 0.2‰ SMOC) reflecting deeper groundwaters but still with little evidence of water-rock interaction; this also in accordance with earlier discussions.

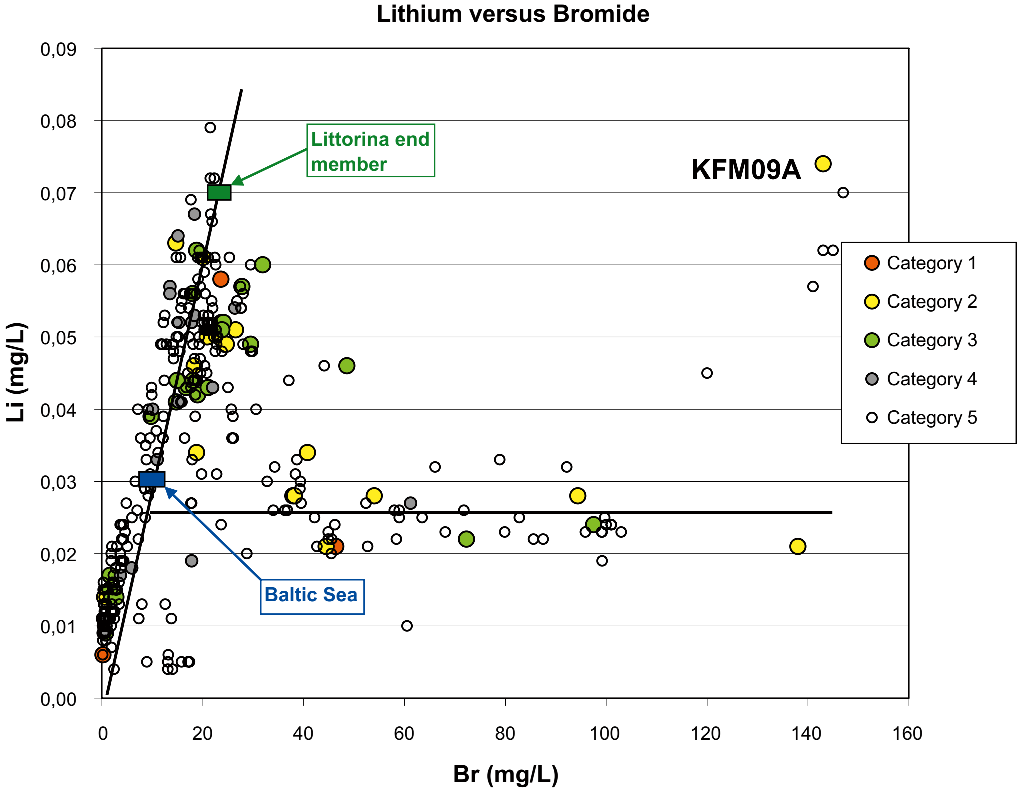


***Figure 5-53.** Plot of lithium versus bromide (categories 1–5) for the Forsmark site showing two groundwater evolutionary systems: a) a shallow (0–600 m), younger brackish marine (Baltic/Littortina) system, and b) a deeper (600–1,000 m), older non-marine system.*

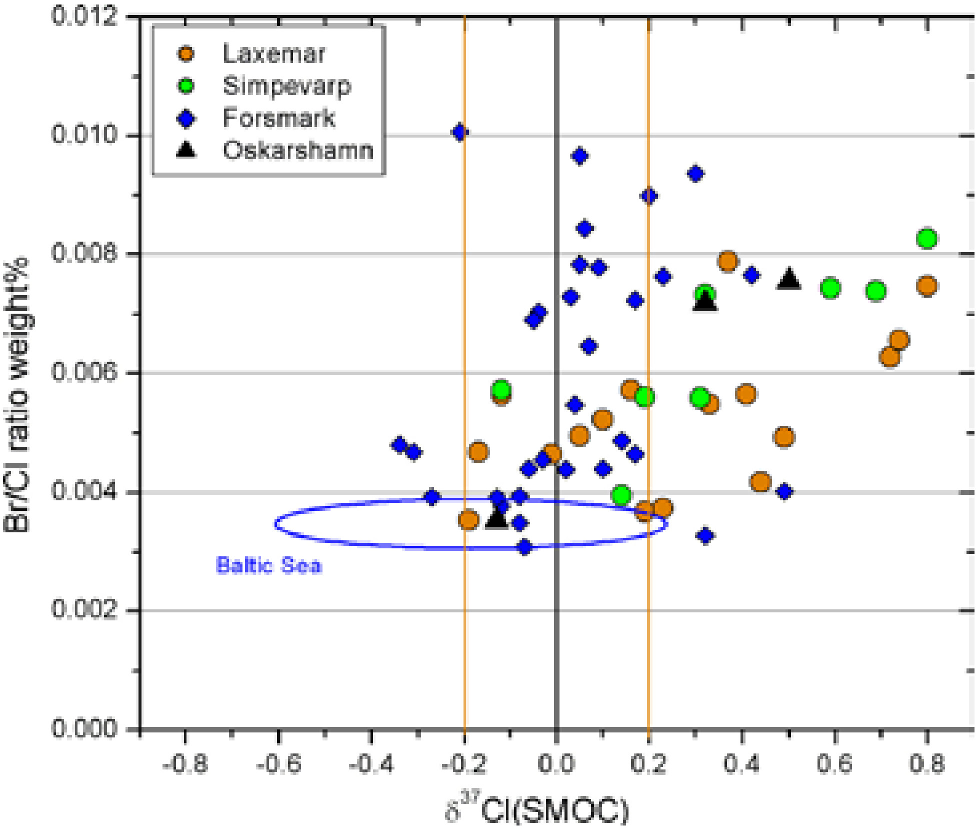


Figure 5-54. *Plot of δ^{37}Cl versus Br/Cl ratio (categories 1–4) in groundwaters from the Laxemar, Simpevarp and Forsmark sites; the extent of the modern Baltic Sea waters are also shown from the Laxemar-Simpevarp and Forsmark areas. (Vertical brown lines represent an analytical uncertainty of around ±0.2‰ SMOC).*

Stable δ^{18}O and δ^{2}H data have been used in the Canadian Shield studies to differentiate deep brines from younger, shallow derived groundwaters. The distinguishing feature of the deepest groundwaters from the Laxemar subarea and Olkiluoto (with a weak suggestion from the deep Forsmark groundwaters), in common with the Canadian brine plots, is the characteristic deviation trend above the GMWL (enrichment of δ^{2}H) which increases with increasing salinity. This has been discussed, among others, by Frape and Fritz (1987) who considered this as an indication of very intensive water-rock interactions under long residence times.

The trend towards enriched δ^{18}O (and δ^{2}H) values with increasing salinity is indicated for Laxemar, Oskarshamn and Olkiluoto (Figure 5-55). The enriched δ^{18}O values associated with the shallower Forsmark groundwaters is typical for the brackish marine (mostly Littorina) type groundwaters.

5.9.4 Shallow freeze-out brines

The possibility of seawater freeze-out processes contributing to the deep brine component in the Fennoscandian groundwaters has been addressed in section 5.7. Freeze-out processes have probably occurred during permafrost conditions resulting in the propagation of a freezing front down into the bedrock, the depth of penetration being limited by several factors including density traps, decreasing transmissivity and an increased lack of escape routes. Ultimately, this will lead to residual fluids being forced into low transmissive areas adjacent to the main transmissive pathways, i.e. dead-end pathways; microfractures; matrix porewaters etc. These ‘traps’ thus provide the most promising source of undiluted residual fluids and potentially providing the best evidence of freeze-out processes. Without these traps the saline residual fluids

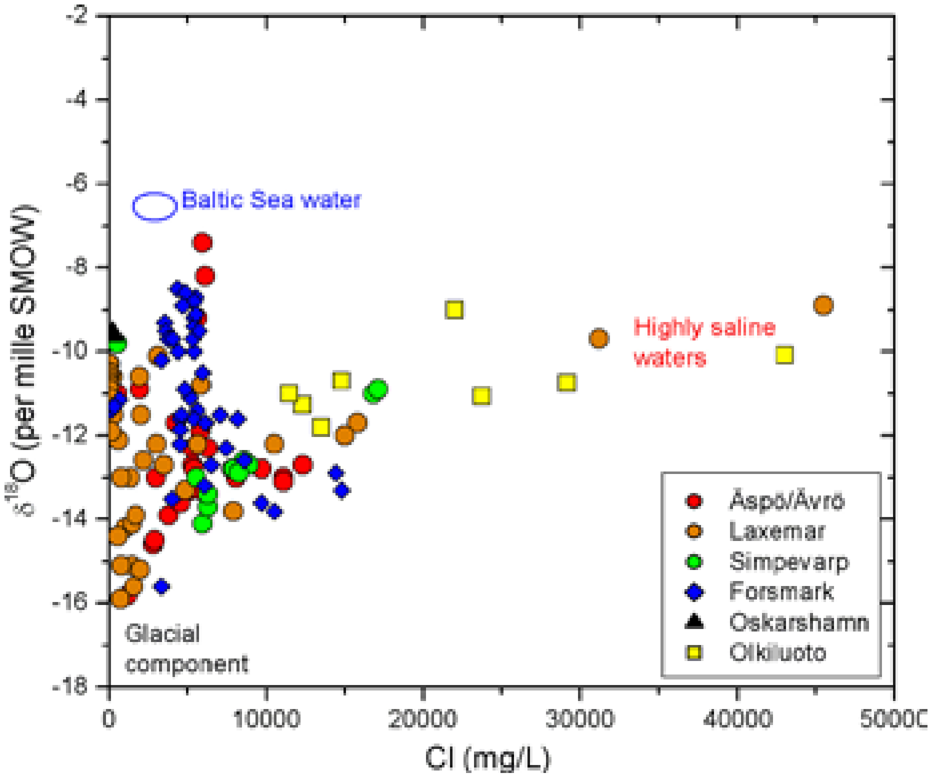


Figure 5-55. *δ^{18}O versus Cl (categories 1–4) for the Fennoscandian sites.*

will become diluted and eventually flushed out of the more transmissive zones and fractures during decay and melting of the permafrost layer and during subsequent land rise. Groundwaters from such sources should not only be characterised by high salinities, but also be analysed for freeze-out indicators such as enriched signatures of δ^{11}B, δ^{18}O and δ^{2}H (and possibly δ^{37}Cl) due to fractionation during freezing. These isotopes have been applied to the groundwaters sampled at Forsmark and used to search for evidence of freezing during periglacial times. Collectively, however, they have not produced any convincing evidence that freeze-out processes have occurred. Further strategic drilling and careful sampling in low transmissive bedrock volumes may show otherwise.

Although there is some possibility that fracture calcites have formed under cold climate conditions in the upper approximately 200 m of bedrock at Forsmark, there is no direct evidence that such formation occurred during freeze-out of bedrock groundwaters under permafrost conditions.

The incursion of different water types and subsequent mixing processes since the last deglaciation have, in all probability, diluted or masked to varying degrees many of the relevant isotopic groundwater signatures that may have existed. Furthermore, fracture filling calcites may have been precipitated or dissolved at various stages, or maybe they still retain evidence of palaeoevents in the form of fine coatings or zones too small to quantify.

5.9.5 Summary and conclusions

Despite the overall lack of data at depths greater than 1,000 m from the selected Fennoscandian sites (with the exception of the Laxemar subarea) there are strong indications that:

- Ca(Na)-Cl groundwaters of deep origin are common throughout the investigated sites.
- True brines (> 100 g/L TDS) have not yet been sampled because of the restricted depth of the drilling campaigns.

- Under undisturbed conditions these deep saline waters have migrated upwards by molecular diffusion processes and mixed with younger, downward moving groundwaters driven advectively by hydraulic gradients responding to surface topography. This latter degree of mixing is site specific, but is most prevalent to around 300–500 m depth, for example at Forsmark and Simpevarp. At greater depths diffusion processes dominate.
- These mixing processes, and degrees of mixing, are clearly indicated from hydrochemical and isotopic considerations.
- The deep saline groundwaters of the Laxemar-Simpevarp group of sites show significant water-rock interaction enrichment with increasing depth which suggests an affinity to a non-marine origin, although a non-marine/old marine mixing origin cannot be excluded.
- Several indicators suggest that the deep groundwaters at Forsmark show a different evolutionary trend, for example, there appears to be less extensive evidence of water-rock interaction enrichment processes.
- Certain hydrochemical parameters (e.g. Ca/Na, Ca/Mg and Br/Cl ratios) reveal similarities between the Fennoscandian sites and the Sudbury Mine brines in the Canadian Shield.
- Laboratory studies show that surface to near-surface freezing of groundwater can produce a residual fluid of high salinity and, because of its high density, may migrate along hydraulically active fractures and settle at great depth in the bedrock.
- Freezing during permafrost conditions almost certainly has occurred in the Fennoscandian Shield and modelling suggests that penetration to depths of 500 m or more, i.e. at least to repository levels, is not impossible.
- Propagation of a freezing front down into the bedrock may force the residual fluid into low transmissive areas adjacent to the main transmissive pathways, i.e. dead-end pathways; microfractures; matrix porewaters etc.
- These low transmissive ‘traps’ are the most promising source of undiluted residual fluids and therefore may provide the best evidence of freeze-out processes.
- These freeze-out residual fluids should not only be characterised by high salinities, but may also show enriched signatures of $\delta^{11}B$, $\delta^{18}O$ and δD; $\delta^{37}Cl$ does not appear to be a sensitive indicator.
- The incursion of different water types and subsequent mixing processes since the last deglaciation have, in all probability, diluted or masked to varying degrees many of the relevant isotopic groundwater signatures that may have existed.
- Although not a major aim of the hydrogeochemical programme, available evidence to the origin of the brine component in the sampled and characterised groundwaters is not immediately obvious and a more sophisticated and well planned approach would be required, for example, an extended programme of drilling to much greater depths and the application of lithium isotope systematics.
- Nevertheless, low transmissive (decreasing flow to stagnant) conditions accompany greatest salinity at each site at depths which are site specific. For example, at greatest depths in recharge areas (e.g. Laxemar subarea), shallower depths in discharge areas (e.g. Simpevarp peninsula) and also in ´shielded´ areas such as Forsmark where structural entities (e.g. bedrock ‘aquifer’ effects) effectively prevent active recharge into the bedrock over large areas.
- The long-term hydrochemical stability of these high saline groundwater environments is supported by ^{36}Cl age dating which indicates a minimum age of around 1 Ma at all the Fennoscandian sites addressed with the exception of Oskarshamn which was not included in the dating programme.

5.10 Groundwater residence time

5.10.1 Background

Groundwater residence time is sometimes confused with the 'age' of a groundwater. As pointed out by /Clark and Fritz 1997/: 'Only tritium is part of the water molecule and can actually 'date' the water. All other dating methods rely on dissolved constituents whose abundance in water is controlled by physiochemical and biological processes.' In addition: 'Hydrodynamic mixing and convergence of groundwater flow paths integrate a variety of recharge origins and ages. Only in well-defined and usually regional artesian aquifers will age gradients along the flow path be preserved'. The hydrogeologic occurrences in a fractured crystalline environment are complex and a straight forward determination of the water residence time is hardly possible based on a single method. In contrast, the various methods relying on radioactive decay of a specific substance and/or water-rock reaction kinetics have to be applied complementary in order to derive an 'average residence time' of the water body of interest.

A key factor in understanding past and present groundwater evolution in the Forsmark area is to constrain the average residence time for each of the major groundwater types. This can be approached qualitatively in terms of the major and trace element compositions of the groundwaters, i.e. based on aspects of water/rock reaction kinetics. Considering different groundwaters that have evolved in a similar geologic environment such as the granitic rocks at Forsmark, a greater groundwater mineralisation can be indicative of a greater residence time (i.e. higher contents of dissolved species as a result of water/rock interaction). Stable isotopes, such as ^{2}H, δ^{18}O, ^{11}B/^{10}B, ^{37}Cl, δ^{13}C, δ^{34}S and ^{86}Sr/^{87}Sr, may also give qualitative information on residence times, such as indications of climate change during recharge etc. On a more quantitative level, because of their known half-life decay character, the radioactive isotopes of ^{3}H, ^{14}C, and ^{36}Cl and non-radioactive ^{4}He are used in the hydrochemical evaluation.

5.10.2 Qualitative information of residence time

Granite and granodiorite comprise the main rock types within the Forsmark target volume. The major rock-forming minerals susceptible to groundwater reaction and alteration are K-feldspar, plagioclase, quartz and micas (biotite/muscovite), giving rise respectively to the redistribution and potential concentration in the rock matrix porewaters and fracture groundwaters of, for example, commonly Na, K, Ca, Rb, Ba and Sr. With decreasing flow to stagnant conditions at increasing depth, accompanied by greater water/rock interaction, these constituents should also increase in concentration accordingly. The amounts of trace elements such as Sr, Rb, Cs and Li in groundwaters are rock dependent but they all show a tendency to increase in concentration with depth when away from the influence of the brackish marine Littorina type groundwaters. These groundwaters tend to complicate depth trends at shallower depths, often masking them.

Calcium, sodium and strontium

Calcium and sodium

The behaviour of calcium and sodium has been chosen to illustrate qualitatively the present variation in groundwater residence times in the Forsmark area. Figure 5-56 shows the variation of calcium and sodium with depth and Figure 5-57 shows the relationship between calcium and sodium. The data have been subdivided into four groundwater compositional groups: Fresh non-marine, Mixed type, Brackish marine (Littorina) and Brackish to Saline non-marine; a Transition type is also recognised. The Mixed type contains components of Littorina and/or Baltic waters and such mixtures generally represent the effects of perturbations, both natural and anthropogenic. The transition type refers to mixtures of brackish marine (Littorina) and brackish to saline non-marine groundwaters, which may also be partly anthropogenic in origin. Sodium, in particular, helps to demarcate the brackish marine (Littorina) from the brackish to saline non-marine groundwaters (Figure 5-57).

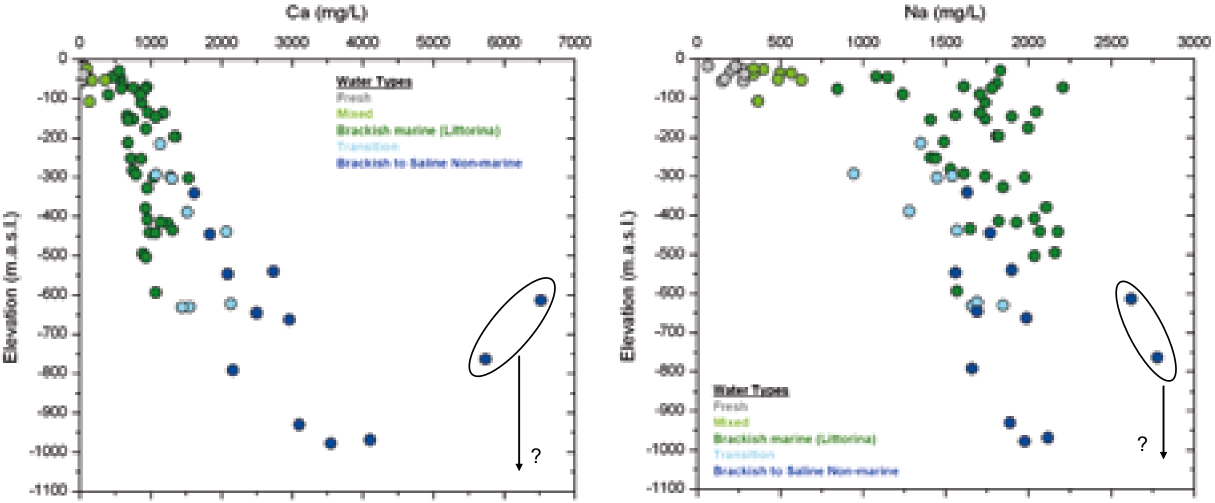


Figure 5-56. *Calcium and sodium plotted against elevation ; probable repositioning of samples KFM07A and KFM09A is shown. (Categories 1–3 + updated data).*

The overall trend of increasing calcium concentration (Figure 5-56) with depth is fairly uniform, albeit broad, for all groundwater types. The anomalous saline groundwater data from boreholes KFM07A and KFM09A are considered to reflect upconing effects (Follin et al. 2007a) which occurred during drilling/sampling, and therefore represent deeper, more evolved groundwater types than indicated by their sampling position shown in the plots. This is supported by higher calcium, sodium (Figure 5-56) and chloride contents (Figure 5-59) which support greater depths than their plotted depths indicate. This disparity is illustrated by the arrow in the calcium and sodium depth plots.

However, the presence of greater salinity at such intermediate depths may reflect natural effects due to glacial rebound (after the maximum glacial loading). This is indicated by the presence of equally high chloride concentrations in pore water from borehole KFM09B collected at a distance of one metre from a water-conducting fracture, but considerably lower chloride further into the intact rock matrix /Waber et al 2008/. This suggests recent, but long interaction time between a high chloride fracture groundwater and the matrix porewater. With the available data, however, a definitive interpretation cannot be presented that supports either a natural or anthropogenic origin to these anomalous groundwater compositions.

With respect to sodium, a more scattered relationship is apparent, although the brackish marine (Littorina) groundwaters are generally more Na-rich at any one depth. There is no clear increasing depth trend until the brackish, non-marine groundwaters are treated separately, whereupon they show a steady increase in sodium from around 100 m to just under 1,000 m depth, and this increase probably continues to greater depths from which the most evolved groundwaters in boreholes KFM07A and KFM09A originate. In contrast, the brackish marine (Littorina) groundwaters show no clear depth trend, only a constant range of sodium content (around 1,500–2,200 mg/L) extending from close to the surface to around 600 m depth.

That the brackish marine (Littorina) groundwaters represent a different and separate hydrochemical system is further accentuated by Figure 5-57. When the Littorina-type groundwaters and most of the perturbed weak marine groundwater are excluded, the figure shows a good correlation within the brackish non-marine groundwater types suggesting a continuous evolution to depth of increasing water/rock interaction and mineralisation. Also clearly illustrated in Figure 5-57 is the transition from brackish marine (Littorina) groundwaters to brackish non-marine groundwaters which corresponds to the change in dominant ion from sodium to calcium.

Strontium

The distribution of strontium with increasing depth is similar to that of calcium (Figure 5-57), which is not unexpected considering their similar chemistries and sources.

Additional information may be derived from the isotope ratio of strontium, $^{87}Sr/^{86}Sr$, with radiogenic ^{87}Sr being continuously produced by the decay of ^{87}Rb (half-life 5×10^{10}a). In general, average ocean water shows a distinct strontium isotope signature (0.70906; /Faure 1982/) which is close to the measured values in the Baltic Sea waters (0.7092), whereas all other waters show higher strontium isotope ratios indicating contributions of radiogenic strontium; this is explained by water-rock interaction processes involving rubidium-containing minerals such as K-feldspar and biotite.

Strontium isotope ratios ($^{87}Sr/^{86}Sr$) have been measured in groundwater samples from cored and percussion boreholes in the Forsmark area and these are plotted against 1/Sr content in Figure 5-58. The plot also includes the location of certain samples collected outside the candidate area. Strontium isotope ratios lie within the approximate range of 0.716 to 0.727; higher strontium ratio values relate to the brackish marine (Littorina) and mixed groundwater types with a Littorina signature.The brackish to saline non-marine groundwaters plot within a much narrower range of ratio values (0.717 to 0.721).

Figure 5-58 is commonly used to evaluate mixing between different strontium origins; however no significant trends at Forsmark can be observed. The system is very heterogeneous and many types of water/rock processes and possibly complex groundwater mixing behaviour have contributed to this present state. All isotope values deviate from those measured in the Baltic Sea samples (0.7092) in that they have higher radiogenic strontium which in turn is due to water/rock interaction processes which probably include both mineral dissolution and ion exchange (cf. Table 6-2, section 6.5). Water/rock interactions also appear to have erased the once established Littorina Sea signature.

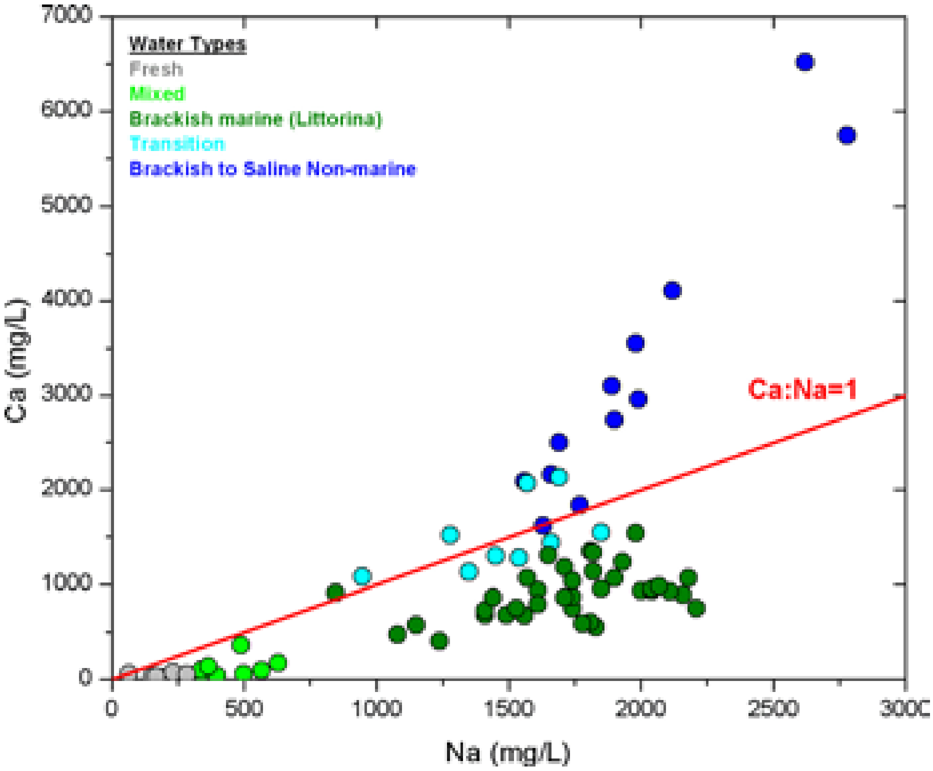


***Figure 5-57.** Calcium plotted against sodium. (F. 2.3 extended updated data included).*

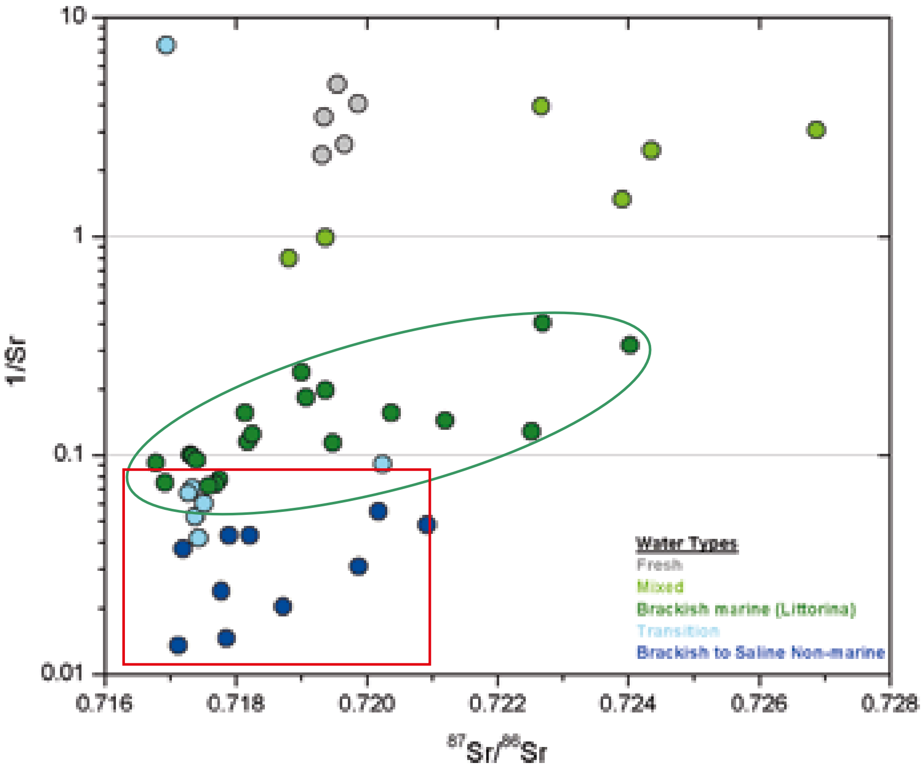


Figure 5-58. *Plot of ^{87}Sr and ^{86}Sr versus 1/Sr in groundwaters from the Forsmark area. Green encircled samples = hanging wall + the upper part of the footwall (fracture domain FFM02); red boxed-in samples = mainly footwall (i.e. fracture domain FFM01).*

In conclusion, the strontium isotopes do not differentiate any increasing trend of water/rock interaction with depth, but rather reflects interaction at all levels within the bedrock.

Chloride and Chlorine-37

Chloride

As mentioned above, other parameters also show an increase in water-rock interaction/concentration with depth, for example, chloride and bromide (cf. section 5.9). In contrast to sodium and calcium, however, chloride and bromide are not the product of increased water/rock interaction, but of exchange at greater depths with the saline porewater contained in the low-permeability rock matrix. As shown in /Waber et al. 2008/, the fracture frequency decreases strongly with increasing depth leading to a much lower groundwater-rock ratio at greater depth. As a consequence, exchange with the saline porewater will occur over a much longer time period and results in highly saline groundwater in the few fractures. Thus, the increase in chloride concentration in non-marine groundwaters indeed represents an increase in residence time of the groundwater.

Permafrost freeze-out processes may have contributed to increases in chloride in the upper approximately 300–500 m of bedrock, but it is uncertain whether these concentrations could have persisted to the present day (cf. section 5.7).

The distribution of chloride with elevation is presented in Figure 5-59; similar plots are included in /Figure A2-8 in SKB 2007/ and /Gimeno et al. 2008, Figures 3.4.2ab/. In accordance with Figure 5-56, the chloride contents of the KFM07A and KFM09A groundwaters would be equivalent to, or greater than 1,000 m when repositioned along the chloride profile. Plots of bromide also show similar increases in concentration with depth (/e.g. Appendix 1, Figure 4-7 in SKB 2005/, and section 5.9 this report) and the same argument as for chloride applies.

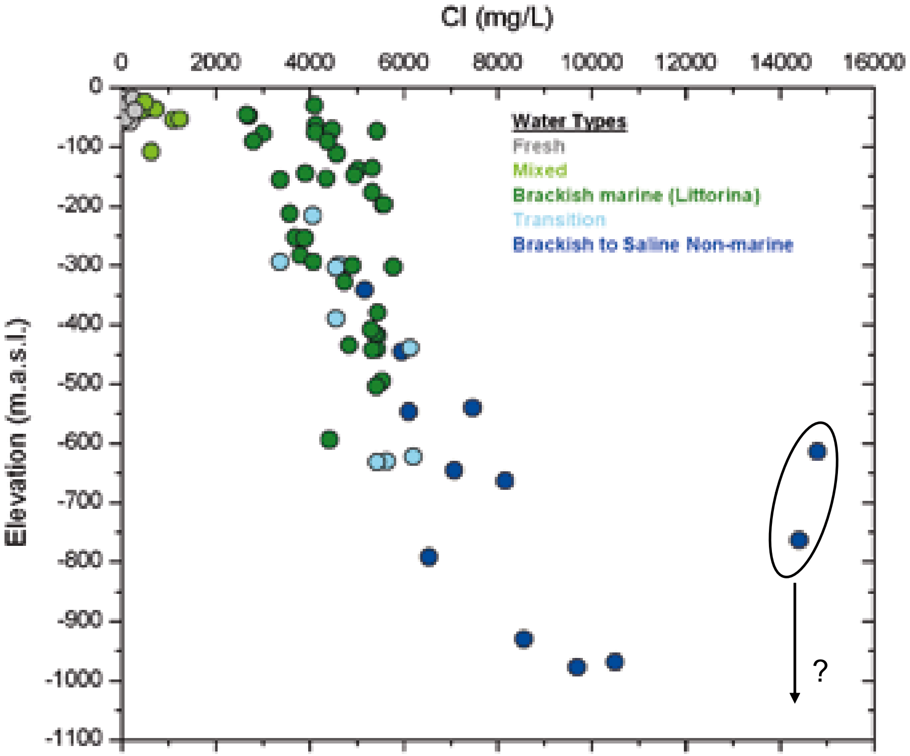


Figure 5-59. *Chloride versus elevation; probable repositioning of samples KFM07A and KFM09A is shown. (Categories 1–3 + updated data).*

Chlorine-37

With respect to stable isotope indicators, variations in the ^{37}Cl/^{35}Cl ratio expressed as δ^{37}Cl (SMOC), may reveal chloride sources of different origin /e.g. Frape et al. 1996, Clark and Fritz 1997, Eastoe et al. 2007/, and this information may suggest the relative age relationships of the different groundwater types. Generally, positive ^{37}Cl signatures in groundwaters are indicative of water/rock interaction chloride sources accumulated over long periods of geological time (e.g. evaporates, hydrothermal chloride), whilst negative signatures indicate chloride sources related to meteoric conditions and chloride isotope fractionation by diffusion processes. Oceanic marine water has a δ^{37}Cl of about 0‰ SMOC, while the much less saline modern Baltic and palaeo-Baltic Seas have a signature of around –0.21‰ SMOC.

Figure 5-60 shows the plotted data with an analytical uncertainty of 0.2‰. Interpretation is restricted as few data plot outside this uncertainty limit, but those positive signatures that lie outside point to the deeper, older, more evolved brackish non-marine groundwaters, which is not unexpected. Likewise, the negative signatures which correspond to shallower depths (approximately 400–500 m) are characteristic of the marine Littorina-type groundwaters.

Stable isotopes (δ^{18}O and δ^{2}H)

Additional qualitative indications of increased water-rock interaction with depth are indicated by the behaviour of the stable isotopes δ^{18}O and δ^{2}H; deep basement groundwaters from Canada (in particular) and Fennoscandia (to a much weaker extent) show a deviation from the Global Meteoric Water Line (GMWL) coeval with increased salinity and enriched in deuterium (^{2}H). This has been already discussed in /Appendix 1, Chapter 14 in SKB 2006a/ and also in detail in /Gimeno et al. 2008, section 2.1.1, Figure 2.1.6/ where data from Forsmark, Laxemar and Olkiluoto were combined to show a general trend of deuterium (^{2}H) enrichment, accompanied by a deviation from the GMWL, at greatest salinity (i.e. depth). This is presented also in

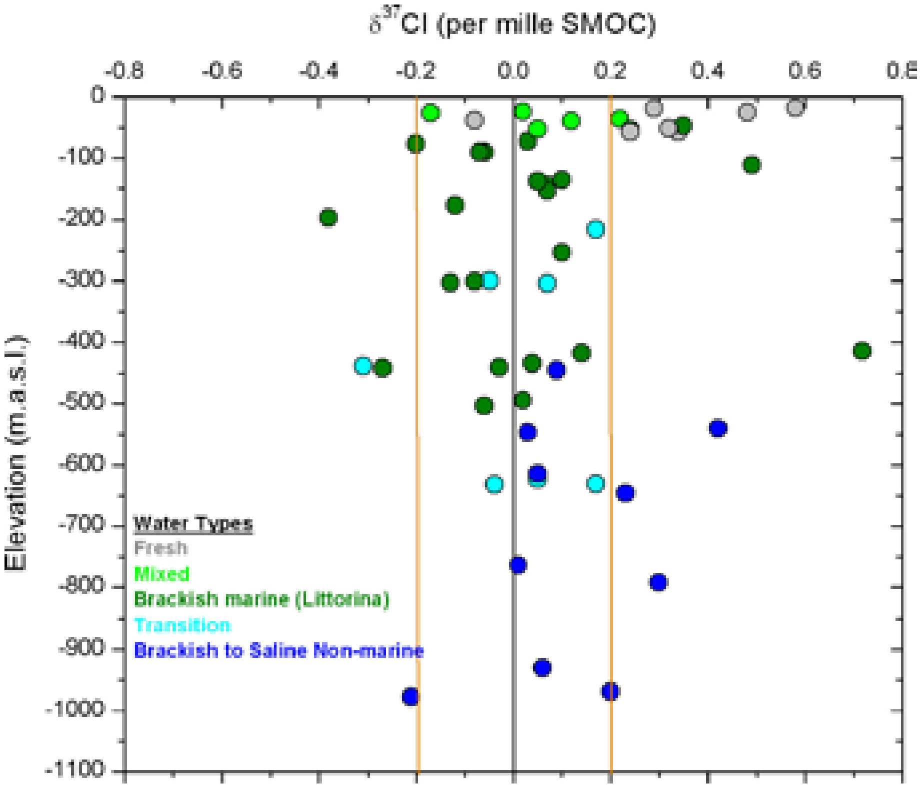


Figure 5-60. *Plot of δ³⁷Cl versus elevation; analytical uncertainty indicated by the vertical brown lines is 0.2‰ SMOC.*

Figure 5-61 were the Forsmark groundwaters show the weakest deviation as highly saline groundwaters are not present at the depths investigated, but this deviation trend is strengthened by the additional Simpevarp (Laxemar subsarea in particular) and Olkiluoto data from deeper, more saline groundwaters. These observations are usually explained by very intensive water/rock interactions under long periods of residence time /Frape and Fritz 1987/ and therefore characteristic of groundwaters of a very old age.

Based on such observations, rock matrix porewaters would be expected also to have similar ^{18}O and ^{2}H enrichments. This is indeed the case for some of the porewaters /Waber and Smellie 2008, Waber et al. 2008/.

Summary and conclusions

In summary, there is a range of qualitative trace and major ion and stable isotope evidence based on depth relationships that generally support hydrogeological observations (cf. discussion in section 7.2.1 and /SKB 2007/) that recent to young groundwaters, some showing signs of perturbation, characterise the upper approximately 100–150 m of bedrock. At these depths, because the hydraulic system is more dynamic, climatic changes have resulted in the cyclic introduction and flushing out of different groundwater types over tens of thousands of years such that residence times for individual groundwater types seem relatively short, i.e. probably some tens to a few thousand years at the most.

Older groundwaters of a distinct Littorina type occur from approximately 150 m to depths of around 300–600 m (depending on the footwall or hanging wall location respectively). From palaeohydrogeochemical evidence these are known to date back to some 5,000–6,000 years (with a period of maximum salinity at 4500–3000 BC). Because of the relatively short residence time these groundwaters have undergone only limited water/rock alteration and most observed changes are due to mixing with other groundwater sources.

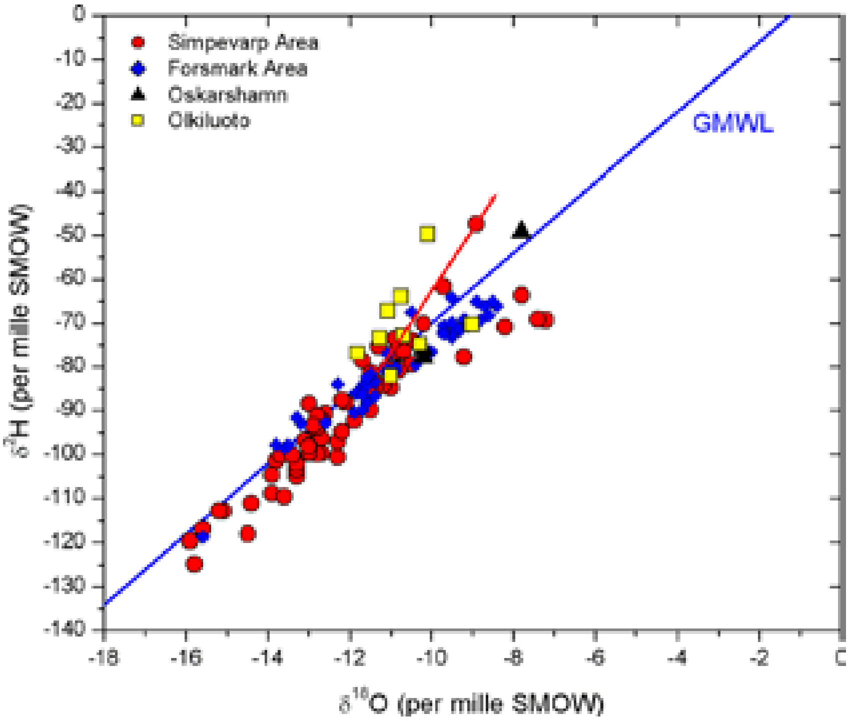


***Figure 5-61.** $\delta^{18}O$ versus δ^2H related to the Global Meteoric Water Line (GMWL) for the Forsmark and Oskarshamn areas. Olkiluoto samples are coloured yellow and follow the same deviation trend from the GMWL as the Simpevarp samples (red arrow).*

Significantly older groundwaters, found at depths greater than around 300–600 m (depending on the location) to around 1,000 m, are characterised initially by brackish non-marine groundwaters which become successfully more mineralised with increasing depth (to saline in type) by water/rock interaction and exchange with the rock matrix porewater. Hydraulic conditions at these depths indicate low to non-existent groundwater flow and suggested residence times would appear to be at least tens of thousands of years and probably more.

No highly saline groundwaters (> 20,000 mg/L Cl) have been sampled at Forsmark but, as indicated by the porewaters /Waber et al. 2008/, there is a high probability that they exist at greater depths and are probably extremely old (i.e. comparable to KLX02 in the Laxemar area).

5.10.3 Quantitative information of residence time

Quantitative information of a groundwater residence time can be derived from short-lived and long-lived radioisotopes. Within the Forsmark hydrochemical programme the radiosiotopes ^{3}H and ^{14}C are analysed routinely. In addition, ^{36}Cl measurements have been carried out on selected groundwaters at a late stage in the programme, essentially to confirm and further constrain the qualitative interpretations outlined above. Helium (^{4}He) gas samples also are routinely collected and analysed, and their input has been used as support, when possible, to the other dating methods. The use of tritium and ^{14}C in Forsmark has been described in earlier reports /e.g. sections 4.4.1 and 4.4.2 in SKB 2005/, whereas the use of ^{36}Cl and ^{4}He has not been previously addressed.

Short residence times

Understanding present-day flow conditions is crucial in determining, for example, the recharge input chemistry to the bedrock, the starting point for much of the bedrock hydrochemical modelling. Meteoric recharge waters of a young age (i.e. less than 55 years), can be traced by its contents of atmospheric thermonuclear tritium from the 1950's still present in the recharge precipitation and shallow groundwaters. Figure 5-62 shows tritium versus depth and includes category 1 to 5 data from percussion and cored boreholes within and close to the candidate area, and category 5 data (i.e. all available data are of low or uncertain quality) from the SFR site. The plot shows a characteristic groundwater decrease in tritium at a depth of around 150 m, which represents the limit of fresh meteoric groundwater and the influence of the shallow bedrock aquifer. The persistent 1–3 TU with increasing depth is due to various sources of contamination (cf. section 4.1.18).

Radiocarbon (^{14}C), with a half-life of 5,730 years, extends the range of detection up to 30,000 years for groundwater residence time. Theoretically, this range should cover comfortably the period since the last deglaciation, in particular confirmation of the Littorina Sea transgression. However, radiocarbon dating is complex and a major problem at Forsmark has been to constrain the ^{14}C input signature to the bedrock, and the reactions involving carbonate dissolution and breakdown of recent and old organic material that will affect the $^{14}C_{(TIC)}$ content in different groundwaters.

Figure 5-63 shows $^{14}C_{(TIC)}$ versus elevation for the Forsmark groundwater samples. The brackish marine waters show $^{14}C_{(TIC)}$ values in the range of 7 to 34 pmC, HCO_3 at 45 to 160 mg/L and $\delta^{13}C$ at –4 to –10‰. Attempts have been made to correct the ^{14}C contents for reactions, mainly based on $\delta^{13}C$. Straight forward calculation from a source term and processes identified, however, has failed to determine the C-14 age; the uncertainty is simply too large (G. Buckau, per. comm. 2007).

Three of the brackish marine waters have also been analysed for ^{14}C (organic) yielding values of 45–53 pmC in samples with $^{14}C_{(TIC)}$ at 13–17 pmC. Lower ^{14}C content in bicarbonate compared with TOC in the same groundwater is usual and normally attributed to reaction involving dissolution of ^{14}C-free carbonates. In conclusion, the radiocarbon analyses support a postglacial origin for the brackish marine (Littorina) groundwater, and 45–53 pmC in the organic phase is in accordance with ages of around 5,000–6,000 years covering the period of maximum salinity during the Littorina stage (4500–3000 BC).

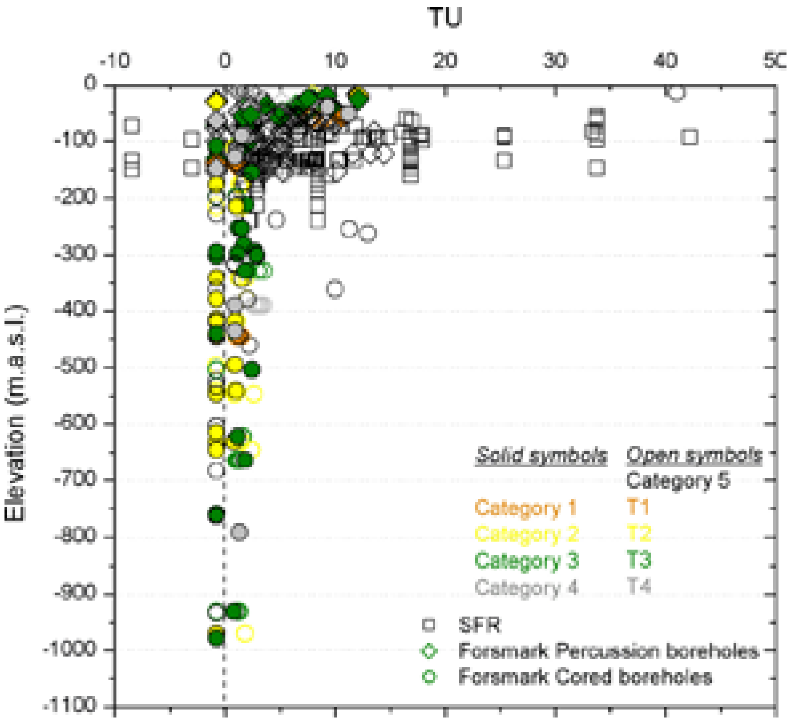


***Figure 5-62.** Tritium versus elevation based on category 1–5 data from percussion and cored boreholes, and category 5 data from SFR.*

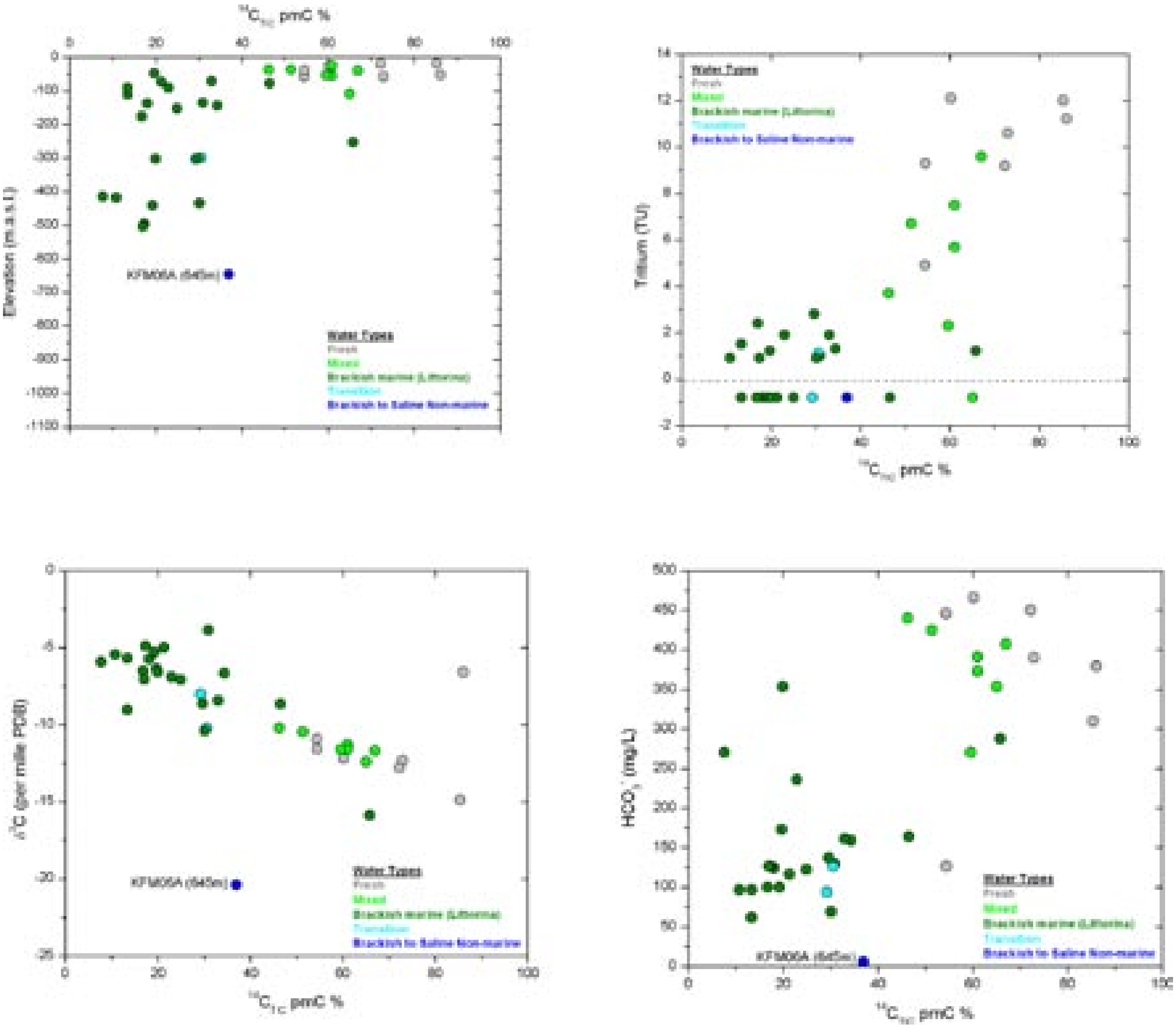


Figure 5-63. *$^{14}C_{(TIC)}$ versus elevation, tritium, $\delta^{13}C$ and HCO_3 content for groundwater samples from Forsmark.*

At Olkiluoto /Pitkänen et al. 1999, 2004/ recognised that the clearest Littorina ^{14}C signatures varied between 20–30 pmC which suggests a total residence time of 4,000–7,500 years. This estimation considered only the influence of recharge and calcite dissolution processes and ignored potential mixing, but nevertheless the estimation lends credence to the palaeo-timescale for the Littorina period derived from other sources.

Long residence times

Chlorine-36

Chlorine-36 with a half-life of 301,000 years and generally simple (conservative) chemistry, is considered very useful for identifying possible origins for the dissolved chloride in ancient saline groundwaters extending back to early Quaternary and late Tertiary times /Andrews et al. 1989ab, Bentley et al. 1986, Andrews and Fontes 1992, Clark and Fritz 1997/.

Radiogenic ^{36}Cl in groundwaters has three sources: a) cosmogenic ^{36}Cl produced in the atmosphere and transported to the hydrosphere via precipitation, b) cosmogenic ^{36}Cl produced in the subsurface by spallation of Cl, K, Ca, and Ar in soil moisture and minerals (epigenic ^{36}Cl) and c) by in situ production caused by the neutron flux produced by the decay of naturally occurring radioelements (i.e. U, Th and K) at greater depth in the bedrock (hypogenic ^{36}Cl). With time the hypogenic ^{36}Cl will accumulate and decay until the rate of production equals the rate of decay (i.e. secular equilibrium will have been achieved) after a period of 1.5 million years.

Groundwaters showing ^{36}Cl at secular equilibrium with the in situ ^{36}Cl production of a specific rock will therefore have been shielded from the atmosphere and resided in this rock for at least 1.5 million years.

Chlorine-36 has been measured in selected groundwaters from the Forsmark site, ranging from the present Baltic Sea to near-surface recharge groundwaters, to deeper brackish marine(Littorina) and brackish non-marine groundwaters, and finally to saline groundwaters sampled from maximum depths (Table 5-3; Figure 5-64).

Table 5-3. ^{36}Cl analyses of selected Forsmark groundwater types.

Sample	Depth (m)	Sec.Mid.Elev. (m)	Chloride (mg/L)	at. ^{36}Cl/at. Cl ratio (10^{-15})	Origin
PFM000062			2,500–2,700	$16 \cdot 10^{-15} \pm 2.4 \cdot 10^{-15}$	Baltic Sea
HFM04	58–66	61.9	55	$160 \cdot 10^{-15} \pm 50 \cdot 10^{-15}$	Fresh meteoric recharge water
KFM02A	490–518	494.97	5,550	$5.9 \cdot 10^{-15} \pm 1.7 \cdot 10^{-15}$	ZFMA2 Brackish marine (Littorina) groundwater
KFM08D	669.7–676.84	540.63	8,000	$36 \cdot 10^{-15} \pm 6 \cdot 10^{-15}$	Brackish non-marine groundwater
KFM08D	828.4–835.54	664.06	7,300	$34 \cdot 10^{-15} \pm 3 \cdot 10^{-15}$	Brackish non-marine groundwater
KFM03A	969.5–994.5	969.14	10,700	$41 \cdot 10^{-15} \pm 4 \cdot 10^{-15}$	Saline groundwater
KFM07A	848.00–1,001.55	~ 760	14,600	$28 \cdot 10^{-15} \pm 7 \cdot 10^{-15}$	Saline groundwater

Units measured = Atoms of Cl-36 per total Cl extracted from groundwater; expressed as: atomic ^{36}Cl/atomic Cl = ^{36}Cl/(^{35}Cl+^{37}Cl).

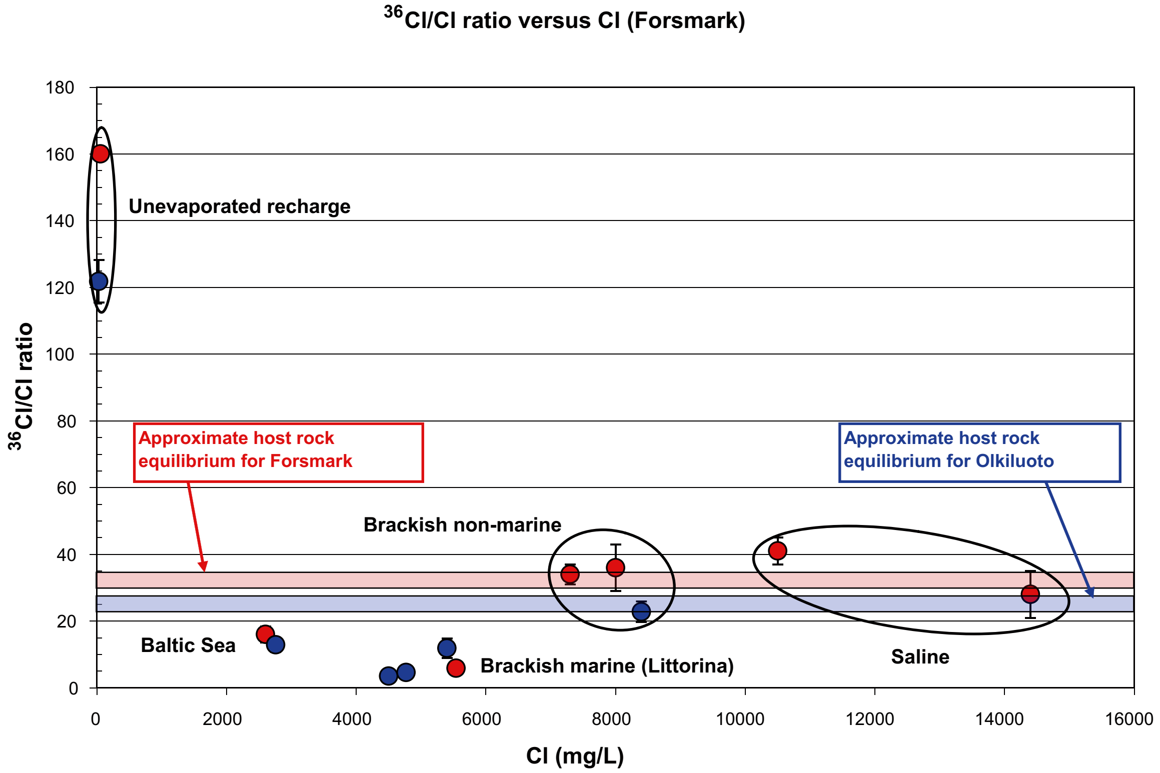


Figure 5-64. *Chloride-36 data from groundwaters at Forsmark (red) and Olkiluoto (blue) compared to secular equilibrium ^{36}Cl/Cl ratios of in situ production in the host rocks (broad horizontal red and blue lines).*

The agreement between the two deeper saline groundwaters and the calculated secular equilibrium in situ production line is less constrained than the brackish non-marine groundwaters but still within the overall uncertainty of the calculations. It is worth noting that both of these saline groundwaters (from boreholes KFM03A and KFM07A) show evidence of upconing from greater depths during sampling, i.e. increasing chlorinity and decreasing $\delta^{18}O$. For both samples, therefore, some mixing with other chloride sources may have occurred during drilling and sampling which may explain the observed small deviations from the in situ production value. Alternatively, the rocks in which these waters originally reside might have slightly different U, Th, K, Gd, Sm etc concentrations and thus a slightly different neutron flux and ^{36}Cl in situ production. Such information, however, is not available and deeper boreholes would be required.

Nevertheless, there is no doubt that the intermediate brackish non-marine and deeper saline groundwaters indicate long residence times which reflect early Quaternary times, and possibly even pre-date the Quaternary age. This is in agreement with: a) earlier ^{36}Cl observations from deep, highly saline groundwater from borehole KLX02 at Laxemar /Louvat et al. 1999/, b) saline groundwaters recently analysed at the Laxemar and Simpevarp subareas (Laxemar F.2.3 Level II Background Report, in preparation), and c) porewater studies /Waber et al. 2008/.

The Baltic Sea water and the brackish marine (Littorina) groundwater behave interestingly. Both types have $^{36}Cl/Cl$ ratios below that of the secular equilibrium with granitic rocks and far below that of fresh meteoric recharge (Figure 5-64). If Fresh meteoric recharge, such as rivers and surface runoff, would be the dominant water source for these Seas, then they would have a higher $^{36}Cl/Cl$ ratio. In contrast, the low ratios measured indicate that most of the chlorine dissolved in the Littorina and the Baltic Sea has resided in the bedrock over long time periods of time and therefore has been shielded from the atmosphere. That the brackish marine (Littorina) groundwater has a lower ratio than the Baltic Sea water indicates that its dissolved chlorine content must have undergone additional shielding from atmospheric input and/or undergone mixing with low ^{36}Cl groundwater from the bedrock. This is consistent with an overall older 'age' of this water type, but not old enough to receive a significant quantity of subsurface produced ^{36}Cl. In agreement with /Gascoyne 2001/ 'this provides strong support for the argument that these (brackish marine) waters are derived from the Littorina Sea.'

The shallow fresh meteoric groundwaters, as would be expected, have enhanced $^{36}Cl/Cl$ ratios indicating atmospheric input.

Helium-4

Helium-4 atoms are continuously produced in rocks by neutralisation of α-particles emitted during the decay of the naturally occurring radioactive elements uranium and thorium /e.g. Andrews et al. 1989ab/. Similar to chloride, helium is conservative, but also chemically inert. Unlike chloride, however, its solubility in the atmosphere is very low and the amount of helium recharged via precipitation is insignificant compared to the in situ produced helium. Generally, radiogenic helium produced in various uranium- and thorium-bearing minerals in the bedrock is readily released to the associated porewater. Once this happens, the helium atoms are transported either by diffusion or advection into the groundwater of neighbouring fractures and eventually released to the atmosphere at the groundwater discharge. By comparing the measured ^{4}He-concentrations in groundwater with the calculated in situ ^{4}He-production rate (based on uranium and thorium concentrations) information about groundwater residence time under closed system conditions, and/or indications of possible external input of helium into the system, can be obtained.

In Figure 5-65 the ^{4}He-concentrations measured in the Forsmark groundwaters are plotted versus the ^{4}He produced over a certain period of time in the bedrock from which the groundwaters were sampled. As can be seen the ^{4}He-concentrations increase from brackish marine (Littorina) to those of the mixed variants, eventually to those of the brackish to saline non-marine groundwaters. For the measured ^{4}He concentration in the brackish marine (Littorina)

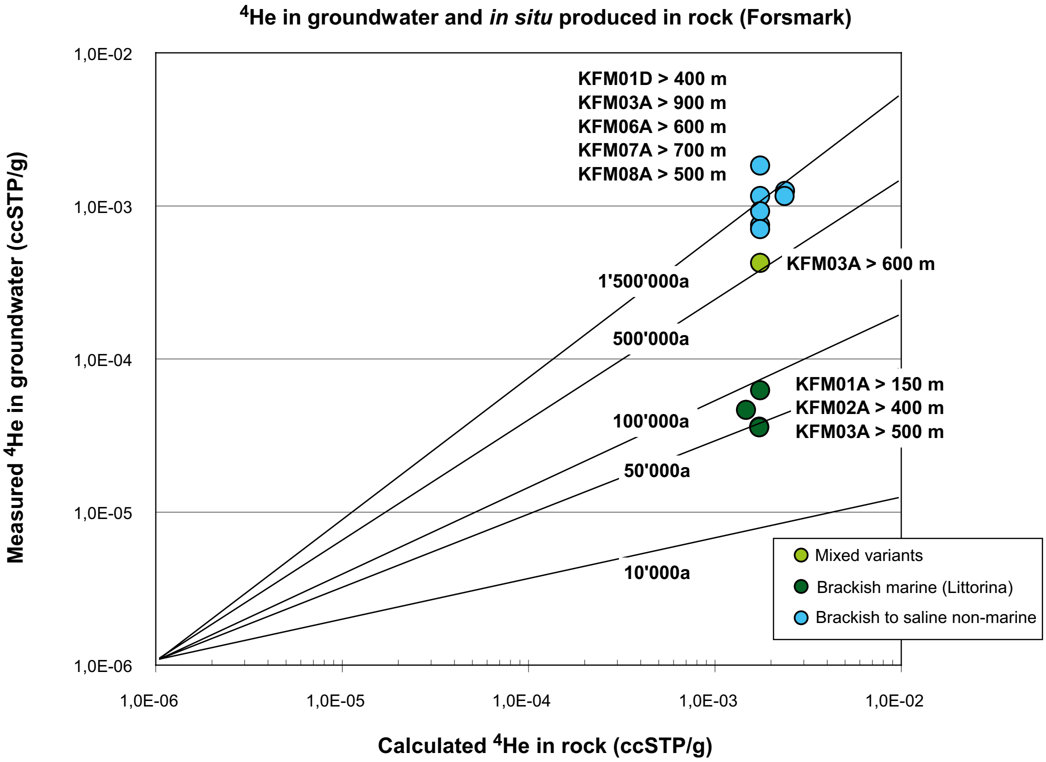


Figure 5-65. *Helium in groundwater and calculated in situ production (model ages neglect flux from great depth).*

groundwaters it would have required about 50–100 ka to produce the equivalent ^{4}He concentration produced by in situ in the rocks by radioactive decay. Even if these Littorina-type groundwaters should contain a certain percentage of a very old component, these calculated time intervals are unrealistically long and, in turn, indicate that there is a substantial helium flux from greater depth.

For the brackish to saline non-marine groundwaters it would require about 1.5 Ma to produce the measured ^{4}He concentration in situ. This is in accordance with the ^{36}Cl data for the two saline groundwaters from greatest depths (KFM07A and KFM03A), where secular equilibrium appears to have been achieved, thus giving an identical residence time. This is strong evidence that at these depths the average groundwater residence time is indeed in the order of 1.5 Ma. At shallower levels, where there may be increased fracture frequency and transmissivity, similar groundwater types with similar ^{4}He concentrations might either receive some helium flux from below, thus leading to an overestimation of their residence time, or ^{4}He might come from only weakly fractured rock portions where localised in situ production may also be occurring, where groundwater flow is also limited, and where the calculated water residence time would therefore be overestimated.

This latter hypothesis is supported by the trends developed between ^{4}He, δ^{18}O and δ^2H, for example, for δ^{18}O in Figure 5-66. Here the ^{4}He concentrations increase from brackish marine (Littorina) to brackish to saline non-marine groundwaters coeval with a simultaneous depletion of ^{18}O (and ^{2}H), i.e. more negative δ^{18}O (and δ^2H) when compared to the Forsmark groundwaters plotted in Figure 5-62. This can be explained by an increasing amount of an old, cold-climate water with a longer residence time and thus higher ^{4}He concentration than the brackish marine (Littorina). A second increase in ^{4}He concentrations is then observed within the brackish to saline non-marine groundwaters, but here under simultaneous enrichment of ^{18}O (and ^{2}H). This indicates the increasingly long residence times of these groundwaters with an increasing proportion of either deep saline or warm-temperature climate infiltration, both consistent with the ^{36}Cl data.

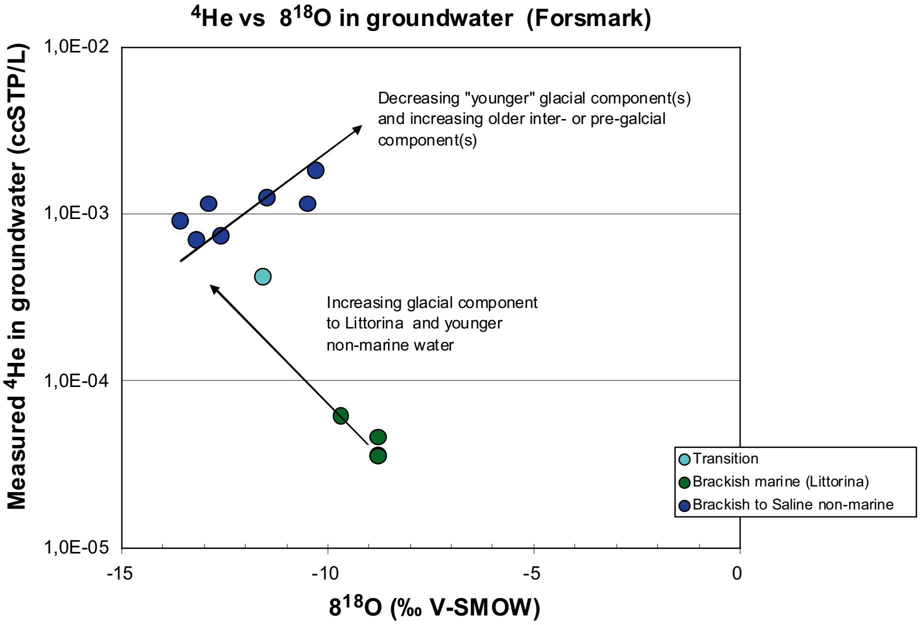


***Figure 5-66.** Helium versus $\delta^{18}O$ showing the different evolutionary trends.*

5.10.4 Conclusions

In summary, there is a range of qualitative trace and major ion and stable isotope evidence, and quantitative isotopic evidence, based on depth relationships that generally support hydrogeological observations. This evidence shows:

- Recent to young fresh groundwaters, some showing signs of mixing with Littorina (and Baltic) sea components, characterise the upper approximately 100–200 m of the bedrock (i.e. the shallow bedrock aquifer). At these depths, because the hydraulic system is more dynamic, climatic changes have resulted in the cyclic introduction and flushing out of different groundwater types over tens of thousands of years such that residence times for individual groundwater types seem relatively short, i.e. probably some hundreds to a few thousand years. This is borne out by tritium and ^{14}C which indicate that near-surface groundwaters have short residence times in the order of only a few decades to a few hundred years. This is in agreement with palaeohydrogeological evidence which indicates land rise occurring at Forsmark some 2,500 years ago, and subsequently establishing meteoric water recharge around 900 years ago.
- Older groundwaters of a distinct Littorina type occur from approximately 200 m to depths of around 300–600 m (depending on the location). The radiocarbon analyses support a postglacial origin for the brackish marine (Littorina) groundwater, and ^{14}C at 45–53 pmC in the organic phase is in accordance with palaeohydrogeological estimations which suggest an age of approximately 5,000 to 6,000 years covering the period of maximum salinity during the Littorina stage (4500–3000 BC). Because of the relatively short residence time these groundwaters have not undergone major water/rock alteration and most observed changes are due to mixing with other groundwater sources, with the addition of microbial modification, silicate weathering and ion exchange processes.
- Significantly older groundwaters, found at depths greater than around 300–600 m (depending on the location) to around 1,000 m, are characterised initially by brackish non-marine groundwaters which become successfully more mineralised with increasing depth (to saline in type) by water/rock interaction, mixing with (unknown) deep saline groundwater, and exchange with the rock matrix porewater. Hydraulic properties at these depths indicate decreasing flow to stagnant groundwater conditions, suggesting residence times that appear to be considerable. From ^{36}Cl and ^{4}He systematics the residence time of the brackish to saline non-marine groundwaters can be shown to extend back to at least 1.5 Ma.

- No highly saline groundwaters (> 20,000 mg/L Cl) have been sampled at Forsmark, but as indicated by the porewaters /Waber et. al. 2008/ there is a high probablility that they exist at greater depths (e.g. KLX02 in the Laxemar subarea) and are at least as old as the shallower, brackish non-marine groundwaters.

6 Palaeohydrogeochemistry of the Forsmark site

6.1 General

Palaeohydrogeochemistry has been an important and integral part of the SKB hydrogeochemical site investigations since the early 1980s. Considerable advances have been made since then based on a greater geological understanding of Quaternary field evidence and on improved laboratory techniques. Such techniques have led to more quantitative isotopic and major and trace element geochemical evidence of palaeo-indicators from different sources including groundwaters, rock porewaters and mineral coatings from water-conducting fracture zones. Furthermore, isotopic systematics have helped determine the residence times of key groundwater and porewater types, providing a time frame to more quantitatively conceptualise the conditions before and after the last deglaciation.

6.2 Quaternary evidence

6.2.1 Background and hydrological implications

The following is taken directly, with only minor modification, from /Follin et al. 2008a/. Quaternary studies have underlined the importance of major crustal movements that have affected and continue to affect northern Europe, following the melting of the latest continental ice, the Weichselian glaciation. These show the interplay between isostatic recovery on the one hand and eustatic sea level variations on the other. The net effect of these two processes in terms of elevation is called shore level displacement /Påsse 1997/.

During the main phase of the last Weichselian glaciation, the global sea level was in the order of 120 m lower than at present, due to the large amounts of water stored in ice /Fairbanks 1989/. In northern Sweden, the heavy continental ice depressed the Earth’s crust by as much as 800 m below its present altitude. A marked improvement in climate took place about 18,000 years ago, shortly after the last glacial maximum and the ice started to retreat, a process that was completed after some 10,000 years. There was a major pause and, in some areas, a re-advance of the ice front during a cold period ca 13,000–11,500 years ago. The end of this period marked the onset of the present interglacial, the Holocene (the last 10,000 years). The ice retreated more or less continuously during the early part of the Holocene.

As soon as the vertical stress started to decrease, due to thinner ice coverage, the crust started to rise (isostatic land uplift). This uplift started before the final deglaciation and is still an active process in most of Sweden. For instance, in the Forsmark area, the current uplift rate is around 6–7 mm per year and within the next 10,000 years the accumulated shore level displacement is predicted to be approximately 40 m /Påsse 1997/. Thus, the hydrological conditions in the Forsmark area are not at steady-state and the site will cease to be a coastal site in the future.

The development of the aquatic systems in the Baltic basin since the last deglaciation is characterised by changes in salinity, which are related to changes in sea level. This evolution has been divided into four main stages /Björck 1995, Fredén 2002/, which are summarised in Table 6-1 and Figure 6-1. The most saline period during the Holocene occurred approximately 4500–3000 BC, when the surface water salinity in the so-called Littorina Sea was 9–14‰ compared with approximately 5‰ today in the Baltic Sea /Westman et al. 1999/.

Table 6-1. Evolution of the Baltic Sea basin since the last deglaciation /after Follin et al. 2008a/.

Baltic stage	Calender year BC	Salinity	Environment in Forsmark
Baltic Ice Lake (not applicable in Forsmark)	13000– 9500	Glacio-lacustrine	Covered by inland ice.
Yoldia Sea (perhaps not applicable in Forsmark)	9500–8800	Lacustrine/Brackish /Lacustrine	At the rim of the retreating inland ice.
Ancylus Lake	8800–7500	Lacustrine	Regressive shoreline from about 140–75 m RHB 70.
Littorina Sea (→ Baltic Sea)	7500–present	Brackish	Regressive shoreline from about 75–0 m RHB 70. Most saline period 4500–3000 BC. Present-day Baltic Sea conditions have prevailed during the last ca 2,000 years.

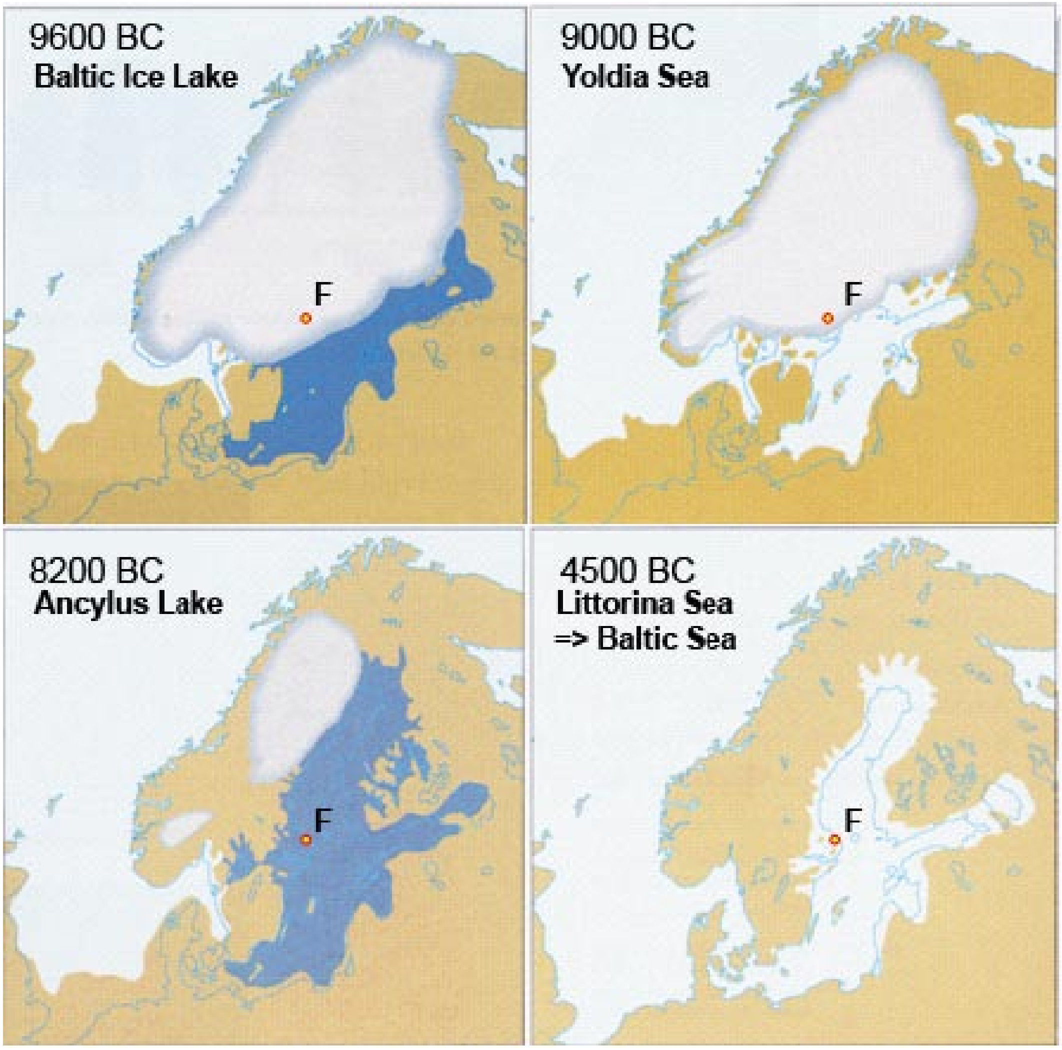


Figure 6-1. Map of Fennoscandia showing some important stages during the Holocene period. Four main stages characterise the development of the aquatic systems in the Baltic basin since the latest deglaciation: the Baltic Ice Lake (13000–9500 BC), the Yoldia Sea (9500–8800 BC), the Ancylus Lake (8800–7500 BC) and the Littorina Sea 7500 BC-present). Fresh water is symbolised with dark blue and marine/ brackish water with light blue. Modified after /Fredén 2002/. The Forsmark area (notated 'F') was probably at the rim of the retreating ice sheet during the Yoldia Sea stage /from Follin et al. 2007/.

6.2.2 Scenario from before the last deglaciation to the present time

Development of permafrost and cryogenic saline water

When the continental ice sheet was formed about 100,000 years ago permafrost formation ahead of the advancing ice sheet probably extended to depths of several hundred metres. This is suggested by present day permafrost in crystalline rock at Lupin Mine, northern Canada, considered to be a remnant from the last glaciation, which extends to around 500 m /Ruskeeniemi et al. 2004/. No convincing evidence of remnant permafrost exists in northern Fennoscandia.

According to /Bein and Arad 1992/ the formation of permafrost in a brackish lake or sea environment (e.g. similar to the Baltic Sea) produced a layer of highly concentrated salinity ahead of the advancing freezing front. Since this saline water would be of high density, it would subsequently sink to lower depths and potentially penetrate into the bedrock where it would eventually mix with formational groundwaters of similar density. Where the bedrock was not covered by brackish lake or seawater, similar freeze-out processes would occur on a smaller scale within the hydraulically active fractures and fracture zones, again resulting in formation of a higher density saline component which would gradually sink (i.e. density intrusion) and eventually mix with existing saline groundwaters.

Whether the volume of high salinity water produced from brackish waters by this freeze-out process would be adequate to produce such widespread effects is presently under debate /section 14.3 in SKB 2006a/. /Pitkänen et al. 2004/ find no evidence in Olkiluoto that the brine component supports a cryogenic formation compared to one of deep elevated temperatures. Furthermore, the cryogenic hypothesis can not explain the change in major ion composition from one different geological environment to another.

With continued evolution and movement of the ice sheet, areas previously subject to permafrost would be eventually covered by ice accompanied by a rise in temperature at the base of the ice sheet and slow decay of the underlying permafrost layer. This decay may have resulted in distinctive hydrogeochemical signatures being imparted to the groundwater and fracture minerals (and potentially to the porewaters given sufficient time). To date, the only apparent hydrochemical indication of freezing in the Forsmark groundwaters is the unusually high $\delta^{11}B$ values (cf. section 5.6); no convincing mineralogical evidence has been found so far.

6.2.3 Scenario following the last deglaciation to the present time

During subsequent melting and retreat of the ice sheet the following sequence of events conceptualised in Figure 6-2 (compare with Figure 6-1) is thought to have influenced the Forsmark site.

When the continental ice melted and retreated (i.e. last deglaciation stage >9500 BC), glacial meltwater was hydraulically injected under considerable head pressure into the bedrock close to the ice margin. The exact penetration depth is still unknown, but depths exceeding several hundred metres are possible according to hydrodynamic modelling e.g. /Svensson 1996/. Any permafrost decay groundwater signatures may have been disturbed or destroyed during this stage.

Different non-saline and brackish lake/sea stages then transgressed the Forsmark site during the period ca 9000 BC to 1500 AD. Of these, two periods with brackish water can be recognised; Yoldia Sea (9500 to 8800 BC) and Littorina Sea (from 7500 BC continuing to the present), with Baltic Sea from 2000 BC to the present. The Yoldia period has probably resulted in only minor contributions to the subsurface groundwater since the water was very dilute to brackish in type from the large volumes of glacial meltwater it contained. Furthermore, this period lasted only for 700 years. The Littorina Sea period in contrast had a salinity maximum of about twice the present Baltic Sea and this maximum prevailed at least from 4500 to 3000 BC; during the last 2,000 years the salinity has remained almost equal to the present Baltic Sea values /Westman et al. 1999 and references therein/. Dense brackish seawater such as the Littorina Sea water was

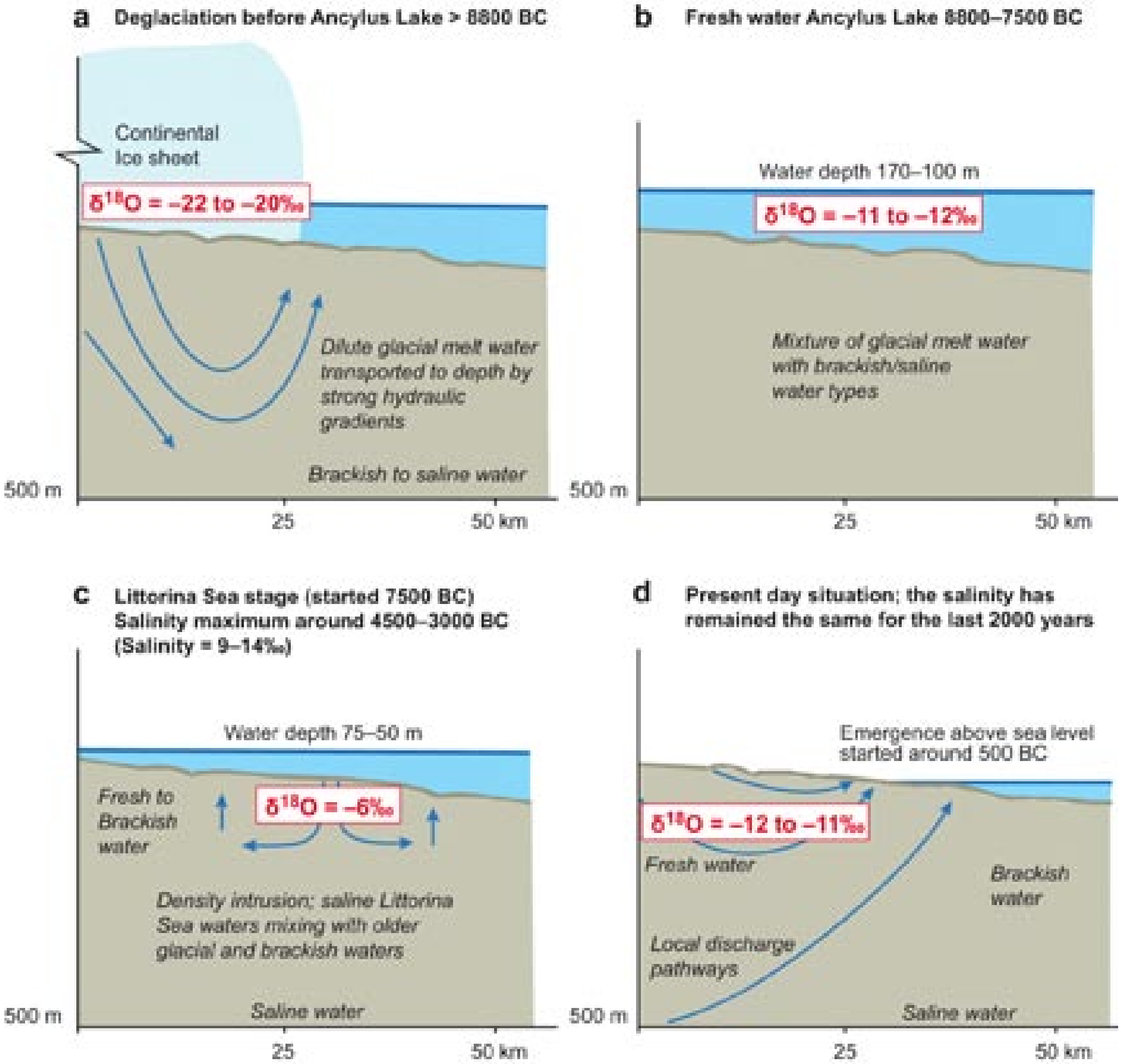


Figure 6-2. Conceptual post-last deglaciation scenario model for the Forsmark area, modified after /SKB 2005/. The figures show possible flow lines, density driven turnover events and non-saline, brackish and saline water interfaces. Possible relation to different known post-last deglaciation stages such as land uplift which may have affected the hydrochemical evolution of the site is shown: a) deglaciation of the continental ice, b) Ancylus Lake stage, c) Littorina Sea stage, and d) present day Baltic Sea stage. From this conceptual model it is expected that glacial meltwater and deep and marine water of various salinities have affected the present groundwater. (Based on the shore line displacement curve compiled by T. Påsse, 2003, per. comm.) and information from /Fredén 2002, Westman et al. 1999, SKB 2002, Hedenström 2003/.

able to penetrate the bedrock resulting in a density intrusion which affected the groundwater in the more conductive parts of the bedrock. The density of the intruding seawater in relation to the density of the groundwater determined the final penetration depth. As the Littorina Sea stage contained the most saline groundwater, it is assumed to have had the deepest penetration depth, eventually mixing with preglacial groundwater mixtures already present in the bedrock.

When the Forsmark region was later raised above sea level starting some 2,500 years ago, fresh meteoric recharge water subsequently formed a lens on the surface of the saline water because of its low density. As the present topography of the Forsmark area is flat (i.e. characterised by a weak hydraulic head), and the the time elapsed since the area was raised above sea level is short, the flushing out of saline water has been limited and the freshwater lens remains still at shallow depths (from the surface down to 25–100 m depending on hydraulic conditions).

Many of the natural events described above may be repeated during the lifespan of a repository (thousands to hundreds of thousands of years). As a result of the described sequence of events, brine, glacial, marine and meteoric waters are expected to be mixed in a complex manner at various levels in the bedrock, depending on the hydraulic character of the fracture zones, groundwater density variations and borehole activities prior to groundwater sampling.

6.3 Hydrochemical evidence

Key ion-ion and isotope plots help to restrict the main groundwater groups to specific depth intervals which generally reflect increasing age with increasing depth and in turn also indicate different hydrogeological environments (cf. section 5.8).

Figure 6-3, based on Category 1–5 data from percussion and cored boreholes, and Category 5 data from SFR, show a characteristic groundwater decrease in tritium at depths of around 150 m. This represents the limit of fresh, meteoric recharge waters of a young age (i.e. less than 55 years), based on the amounts of atmospheric thermonuclear tritium from the 1950s still present in the recharge precipitation and shallow groundwaters. The persistent 1-3 TU with increasing depth is due to various sources of contamination (cf. section 3.2.4 for discussion).

These tritium data are supported by the ^{14}C data which show a corresponding increase (cf. section 5.8.1). For much of the target area the sharp transition between tritiated (young) and non-tritiated (> 55 years old) groundwaters is due to the effect of the shallow bedrock aquifer comprising subhorizontal fractures and sheet joints of high transmissivity mainly at depths of 50–150 m. This aquifer serves to quickly flush these young recharge waters towards the Baltic Sea to the north-east, and also limits active recharge into the underlying, less conductive bedrock.

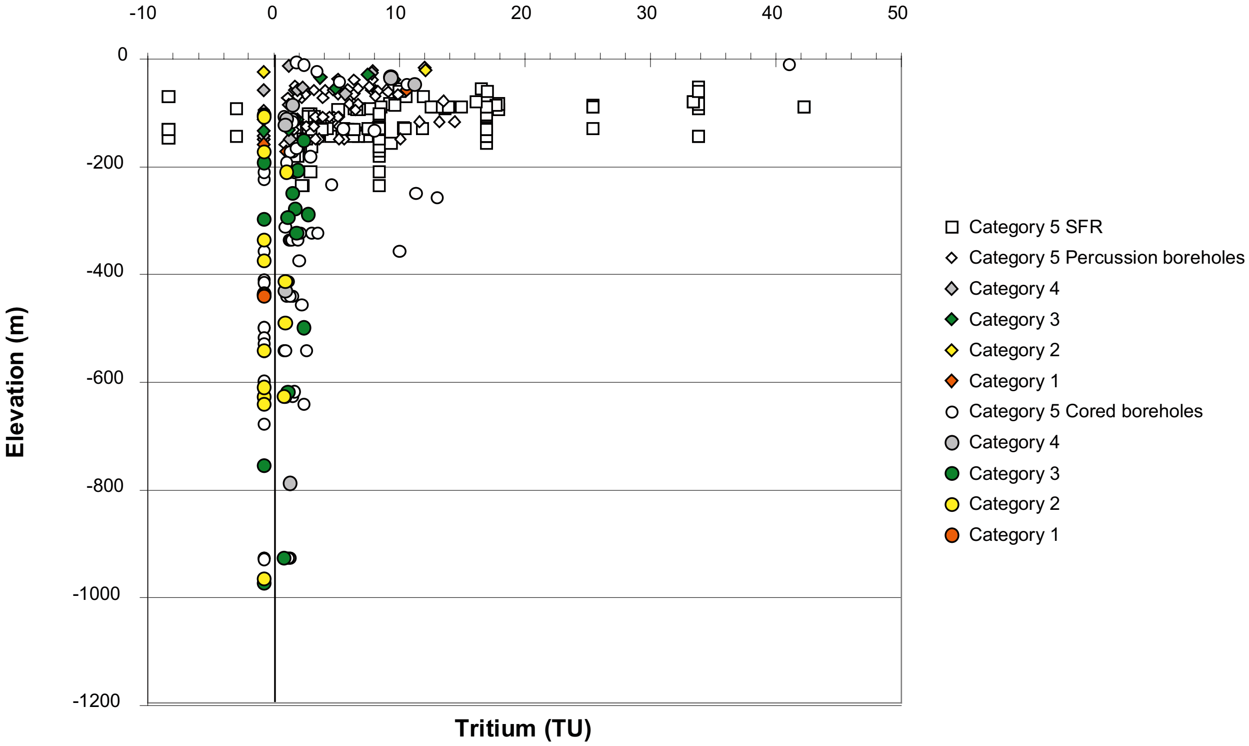


Figure 6-3. *Tritium versus elevation based on Category 1–5 data from percussion and cored boreholes, and Category 5 data from SFR.*

Figure 6-4 plots δ^{18}O against elevation to show the distribution of cold climate input to the Forsmark bedrock. δ^{18}O shows a spread of values similar to tritium in the upper ~150 m (–12 to –8‰ V-SMOW). This mainly reflects localised mixing of meteoric recharge water with brackish marine (Littorina) groundwaters or present Baltic Sea water which occur close to the surface in places. This mixing may be natural or due to anthropogenic reasons such as borehole activities. Some samples also show values lower than –12‰ V-SMOW which may be due to limited pockets of glacial melt water still residing in the upper part of the bedrock. At depths greater than ~150 m two trends can be distinguished: a) one group of values between –12 to –9‰ V-SMOW extending down to around 500 m (and in reality little difference from the shallow meteoric recharge waters) with no clear evidence of variation with depth, and b) another group showing a gradual depletion with depth (–14 to –12‰ V-SMOW) from around 500 m to maximum depths sampled.

The former group corresponds mainly to the brackish marine (Littorina) groundwaters (also containing portions of glacial melt waters), and the latter group to the brackish to saline non-marine groundwaters. These δ^{18}O data collectively indicate,that a cold climate water component persists within the brackish non-marine and deeper saline groundwaters, and also within the Brackish marine (Littorina Sea) type groundwaters (cf. Figure 6-6). Any meltwater from the last deglaciation in the Littorina-type groundwaters, however, will be partly or completely masked by the enriched δ^{18}O signature of these groundwaters

This δ^{18}O distinction with depth also reflects the change to lower transmissivity at 500–600 m associated with the gently dipping deformation zones within fracture domain FFM03.

This hydrochemical grouping of groundwater types related to hydrogeological conditions and depth is a common theme throughout the hydrogeochemical evaluation of the candidate area (cf. Chapter 4), and this is also illustrated in Figure 6-5 which plots Ca/Mg against Br/Cl. This provides the opportunity to differentiate between groundwaters of modern marine (i.e. Baltic Sea), of old marine origin (i.e. Littorina Sea/Old Baltic Sea), and also of non-marine origin (i.e. young fresh recharge waters and older, deeper brackish, saline and highly saline groundwaters).

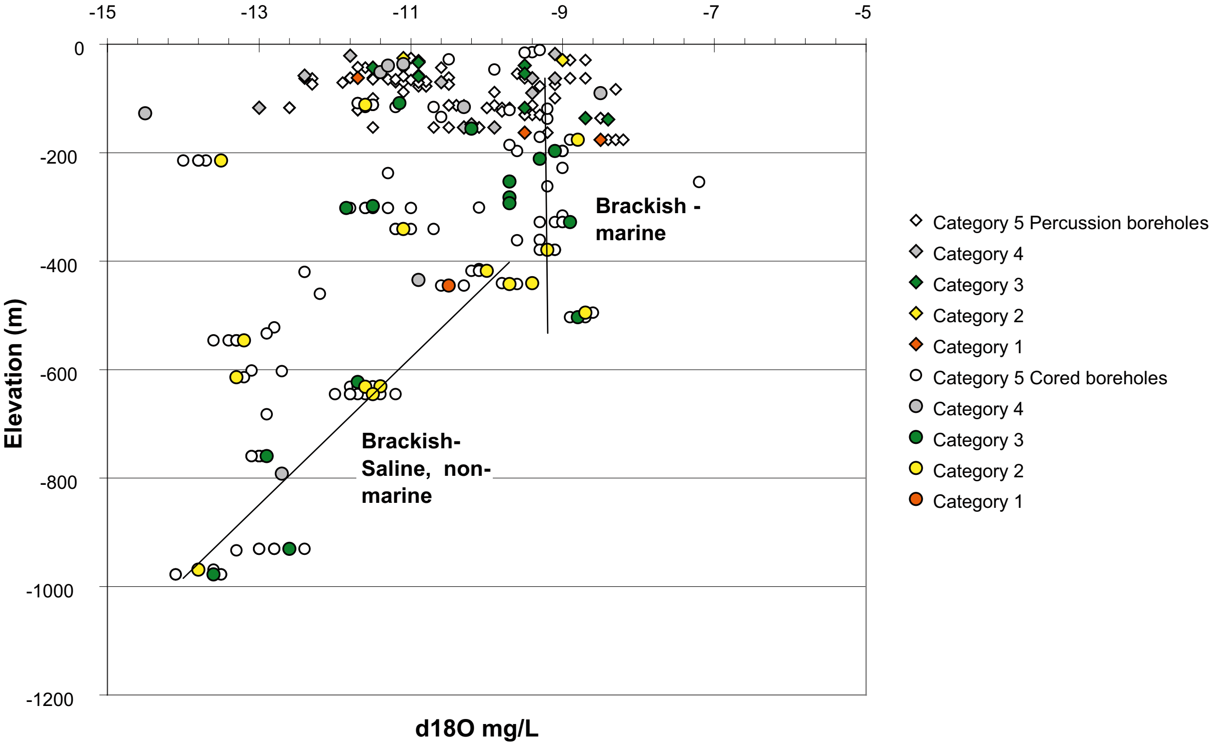


Figure 6-4. *δ^{18}O versus elevation based on Category 1–5 data from percussion and cored boreholes. Two trend lines are indicated; see text for discussion.*

Although Figure 6-5 plots the different groundwater types according to the geological entities from which they were sampled (e.g. fracture domain or deformation zone), for this present discussion it is only the chemistry of the different groundwater types and their distribution that is relevant. In the figure these different types are colour coded as turquoise (Baltic Sea), blue (fresh), green (brackish marine with a weak to strong Littorina component) and red (brackish to saline non-marine). The figure clearly shows the difference between, on one hand, modern, brackish, shallow, marine type groundwaters characterised by a Baltic Sea water signature, and, on the other hand, saline, non-marine, groundwaters acquired at depth in the cored boreholes. Between these two characteristic groups plot most of the groundwater data gathered in the Forsmark area. The red arrow shows the direction towards the deeper, saline, non-marine type groundwaters. To continue even further along this evolution path, if samples were available from greater depths, would probably represent a change to groundwaters with an increasing component of highly saline groundwater. At the other extreme in the plot, some of the data are identified as present day fresh meteoric waters (> 150 m) which are in close contact with older, brackish marine groundwaters characterised by a strong Littorina Sea signature (150–600 m depending on location). At greater depths (500–900 m) there is a transition towards brackish non-marine, groundwaters; some mixing at this transition has resulted in some brackish groundwaters having a weak/dilute Littorina Sea signature. At still greater depths the brackish non-marine groundwaters become increasingly more saline (i.e. saline groundwaters) with the highest value of 14,800 mg/L Cl originating from a deformation zone just outside the target volume.

The complexity of the cold climate component in the brackish marine groundwaters is exemplified further in Figure 6-6, where Littorina-type groundwaters with Br/Cl ratios < 0.0045 and magnesium values higher than 100 mg/L are shown in a chloride versus $\delta^{18}O$ plot. The plot indicates that the uppermost enriched $\delta^{18}O$ values plot along the Oceanic Sea mixing line (i.e. standard ocean composition) joining the Littorina Sea with extrapolated precipitation values at

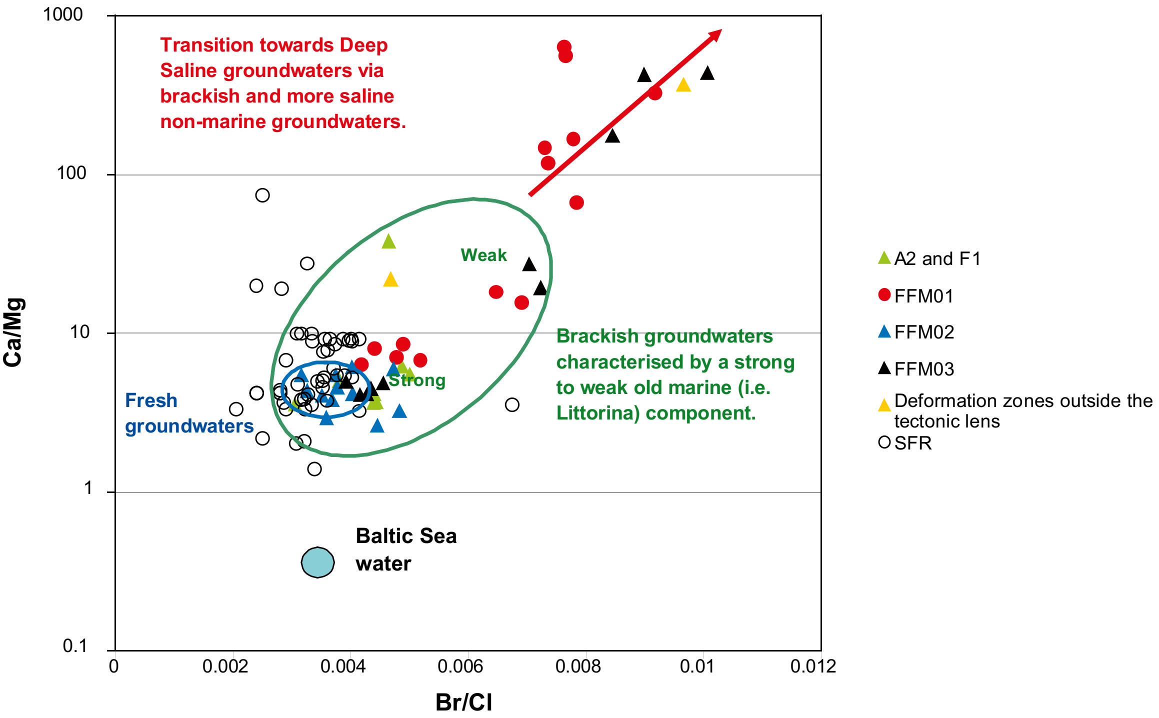


Figure 6-5. Plot of Ca/Mg versus Br/Cl relating to geological entities and differentiating between the saline sources in the main groundwater types constituting the Forsmark site. The approximate limit of fresh and brackish (Littorina-type) groundwaters are ringedin blue and green respectively. Hydrochemical evolution of the groundwater system with increasing depth is along the direction of the red arrow. (Based on /SKB 2005, Appendix 1, Figure 4-30/).

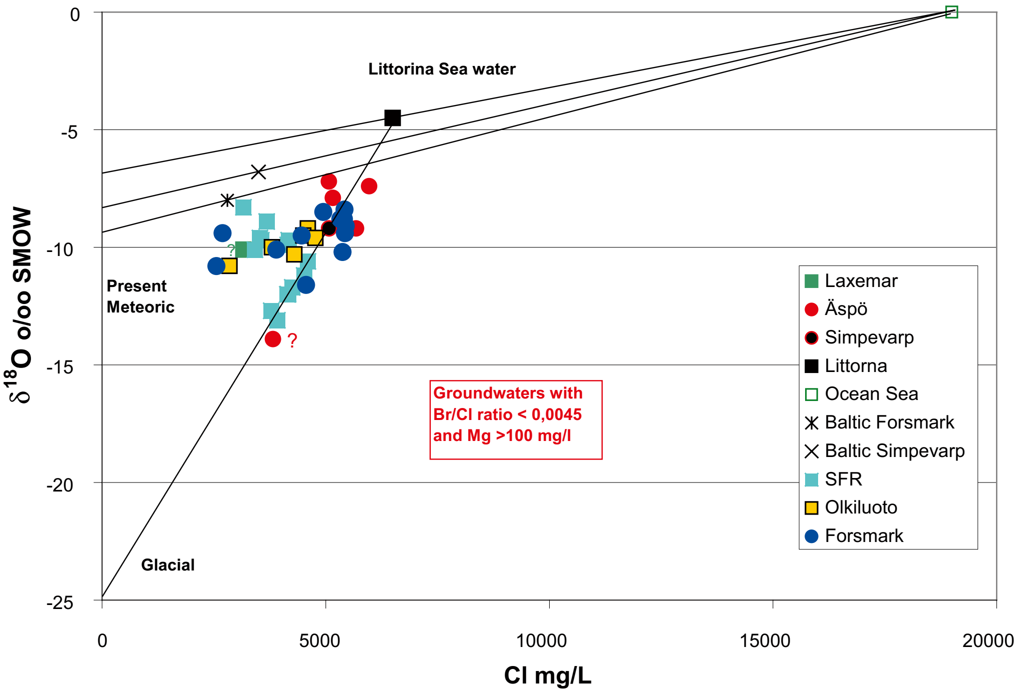


***Figure 6-6.** Chloride versus $\delta^{18}O$ for groundwater with marine components (identified as Br/Cl < 0.0045); all groundwaters show Mg >100 mg/L with two exceptions, one sample from Laxemar and one from Äspö, both denoted with question marks. Most of the plotted groundwaters reflect mixtures of varying proportions comprising the four end members: Last Deglaciation meltwater, Littorina Sea, Baltic Sea and Meteoric waters. (From /SKB 2007, Figure A2-10/).*

that time, and that the Littorina Sea water subsequently mixed with older, last deglaciation dilute meltwaters, as it slowly descended into the bedrock. This has given rise to 'Littorina Sea' waters of varying chemical and isotopic composition in the bedrock at Forsmark and SFR. Two main trends are indicated: a) one indicating mixing between Littorina Sea water and last deglaciation meltwater with a $\delta^{18}O$ of around –25‰ V-SMOW, and b) the other indicating mixing between Littorina Sea, last deglaciation meltwater and modern meteoric groundwater with a $\delta^{18}O$ of around –7‰ V-SMOW. The latter is common for the groundwater sampled in the percussion boreholes whereas the deeper groundwater sampled in the cored boreholes follows the former trend. The mixing of modern Baltic seawater is evident in a few samples.

In summary, this section provides some insight into the evolution of the different groundwater types within the approximate 0–1,000 m bedrock interval sampled, in particular the complexity of the 0–600 m interval in the hanging wall bedrock characterised by transmissive, gently dipping deformation zones. It is mainly via these zones that Littorina Sea water has penetrated by density intrusion to depth, undergoing mixing and reaction during its passage. These observations, in common with M3 calculations /Gurban 2008/, provide strong support to understanding the different palaeo-evolutionary stages that have contributed to the present distribution and chemistry of the Forsmark groundwaters.

6.4 Porewater evidence

Porewater data from rock matrix samples are reported in detail in /Waber et al. 2008/ and also discussed in section 7.2.6. The data from 3 of the 4 boreholes investigated, from the target volume (footwall bedrock segment, including fracture domains FFM01 and FFM02) indicate an upper approximately 100–300 m where there is a variation in porewater chloride but no significant depth trend. From approximately 300 m, however, there is a small but significant systematic increase in porewater chloride to approximately 600 m, followed by a greater increase with depth which varies in magnitude between boreholes. These three depth subdivisions correspond closely to the hydrogeologic properties of the bedrock where active, more dynamic and transmissive conditions (i.e. high frequency of open, water-conducting fractures at close intervals) typify the upper 300 m, followed by a less transmissive intermediate interval from 300–600 m (less frequent open, water-conducting fractures), followed by very low transmissive conditions at depths greater than 600 m (isolated open, water-conducting fractures at large intervals).

These hydraulic properties are, at least generally, also characterised by distinct fracture groundwater and porewater types. This is especially well illustrated in borehole KFM01D (Figure 6-7) which shows: a) some similarity between fracture groundwater and the porewater types within the 0–300 m interval indicating an approach to steady-state diffusions conditions, b) close similarity between fracture groundwater and porewater types at depths greater than 600 m, thereby indicating close to steady-state diffusion conditions, and c) a disparity between the rock matrix porewater and the fracture groundwaters in the 300–600 m interval indicating that more time is required for steady-state conditions to be fulfilled.

These observations suggest different time scales for different palaeoevents, for example: a) close to steady-state conditions down to approximately 300 m suggest recent geological time, i.e. since the last deglaciation some 10,000 years ago, b) close to steady-state diffusion conditions indicated at depths greater than 600 m have been achieved well before the last deglaciation, and c) a significant lack of steady-state from 300–600 m, indicating a perturbed system older than the last deglaciation.

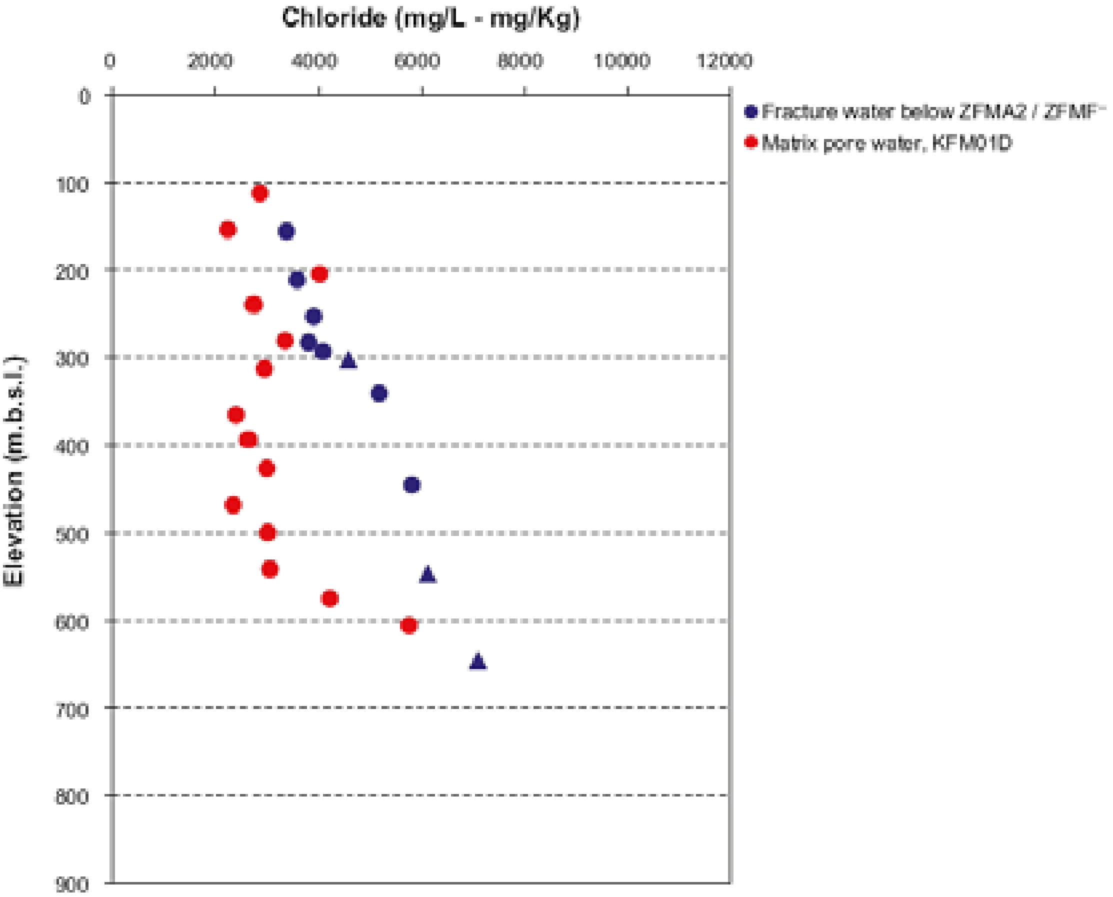


Figure 6-7. Comparison of chloride concentrations between matrix porewater from KFM01D and 'fracture groundwaters' from other borehole sections (boreholes HFM22, KFM01D, KFM06A and KFM08A) representing the same footwall bedrock segment (i.e. including fracture domains FFM01 and FFM02). Groundwater samples assigned to fracture domains and deformation zones are shown as filled-in circles and triangles, respectively. /Olofsson et al. 2007, Figure 7-5/.

The porewater composition in the 300–600 m interval is an important palaeo-indicator to the nature of the bedrock hydrochemical system prior to the last deglaciation. The porewater has around 2,000 mg/L Cl and is referred to as a groundwater of 'Old Meteoric ± Old Glacial ± Saline' type, and is believed to represent a snap-shot of the salinity profile which existed prior to the last deglaciation (cf. discussion in section 6.7).

Porewater stable isotope data are reported with an error of ± 1.5‰ V-SMOW for $\delta^{18}O$ and ± 15‰ V-SMOW for δ^2H /Waber and Smellie 2007/. Compared to chloride, these isotopic data are much more complex to interpret because of their restricted compositional range in the groundwaters. In the extreme case where Littorina Sea waters have mixed with waters with a high glacial meltwater content, the depleted $\delta^{18}O$ signature of the glacial meltwater has been masked largely by the enriched $\delta^{18}O$ signature of the Littorina Sea waters. Caution must therefore be exercised when interpreting low resolution stable isotope data in conjunction with high level resolution chloride concentrations in the porewaters.

6.5 Mineralogical evidence

6.5.1 Background

Fracture mineral studies can provide a palaeohydrological record in crystalline rock essential for the 1 Ma time perspective of interest for a spent nuclear fuel repository. Signatures of older groundwater regimes may have left imprints (i.e. by mineral formation) that can help to interpret the hydrogeochemical evolution. The most commonly precipitated fracture minerals in the crystalline rocks at Forsmark are chlorite, calcite, sulphides and Fe-oxides. Calcite is the mineral best suited for palaeohydrological studies since it precipitates during a wide range of conditions including present day low temperature conditions. Sulphides and Fe-oxides provide important information of the development and evolution of redox fronts.

It is well known that stable isotope and trace element composition of fracture filling calcites can be used as indicators of past and present hydrogeological conditions, for example due to their relative fast response to changes in fluid chemistry and temperature /e.g. Wallin and Peterman 1999, Blyth et al. 2000, Milodowski et al. 2005, Tullborg et al. 2008/. The $\delta^{18}O$ of the calcite depends on the $\delta^{18}O$ value in the fluid responsible for precipitation and the formation temperature, whereas $\delta^{13}C$ gives mainly information on the carbon source and the process involved in the bicarbonate production.

$^{87}Sr/^{86}Sr$ isotopes do not fractionate during precipitation and calcite inherits therefore the $^{87}Sr/^{86}Sr$ ratios from the precipitating fluid. The $^{87}Sr/^{86}Sr$ ratios in the groundwaters and hydrothermal fluids are largely determined by water/mineral interaction and to a lesser degree by the different origins of the fluids (e.g. marine versus non-marine). Since the fraction of radiogenic Sr is steadily growing in the rock and fracture minerals with time, higher $^{87}Sr/^{86}Sr$ ratios in the calcite may reflect younger ages of the calcite.

6.5.2 Calcites

The application of isotope systematics on the Forsmark calcites has resulted in identifying three general types of calcites (Figure 6-8 and Figure 6-9) based on stable isotope composition: a) hydrothermal calcite (Generation 2), b) warm brine-type calcite originating from a fluid influenced by organic material (Generation 3), and c) low temperature calcite precipitated from different groundwaters under temperatures close to the present groundwater temperatures (Generation 4). Calcites of the latter type occur only in small amounts but have been preferentially sampled for stable isotope analyses since they may give information on the latest groundwater evolution in the area.

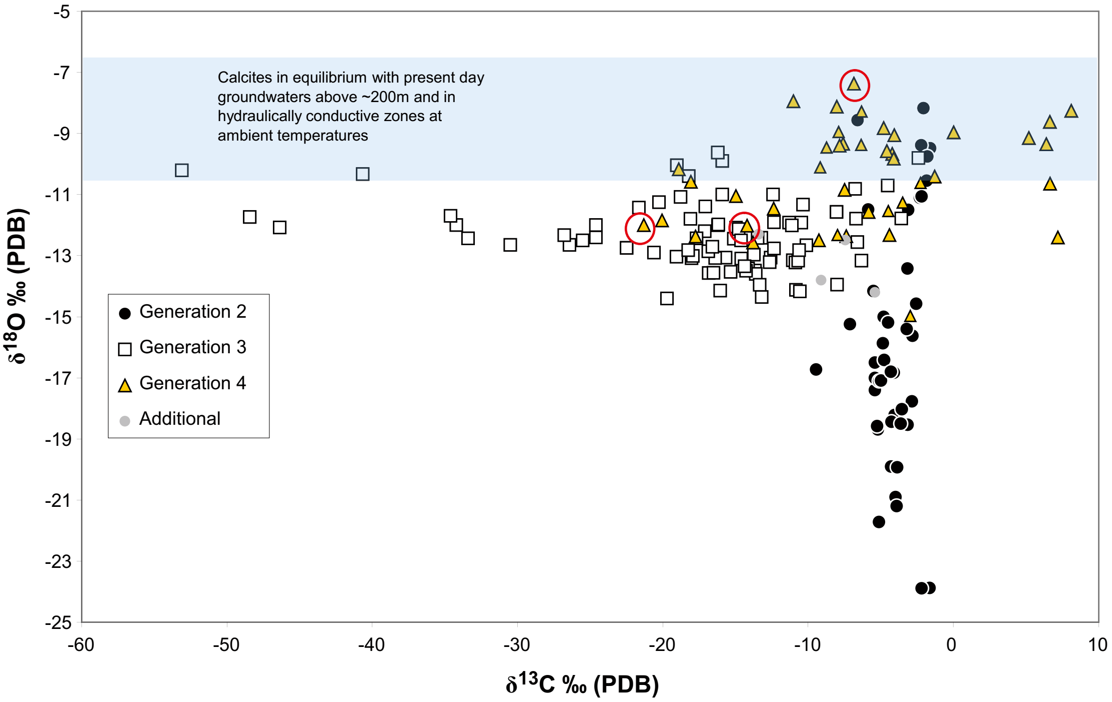


Figure 6-8. *$\delta^{13}C$ versus $\delta^{18}O$ in fracture filling calcite. The isotopic composition of groundwaters above around 200 m and in hydraulically conductive zones are dominated by brackish marine groundwaters (–10 to –8.5‰ SMOW) and, in the upper 100 m, by fresh meteoric water (–12 to –10.5‰ SMOW). For calculation of $\delta^{18}O$ in calcite in equilibrium with these waters, the fractionation formula by /O'Neil et al. 1969/ has been applied at a temperature of approximately 7°C. Calcites marked as 'Additional' have not been possible to relate to the relative sequence of fracture mineralisations. Analytical errors are smaller than the size of the symbols. Three generation 4 calcites with $^{87}Sr/^{86}Sr$ overlapping with present groundwaters are marked with red circles.*

Hydrothermal (Pre-Sveconorwegian to Sveconorwegian) Generation 2 calcites

Generation 2 calcites (Figure 6-8) show relatively small variations in $\delta^{13}C$ with values between –1.6 and –7.1‰ PDB (Pee Dee Belemnite). The majority of these calcites have low $\delta^{18}O$ values (<–14‰ PDB) although calcites showing a shift toward enriched $\delta^{18}O$ values are also found (Figure 6-9). Depleted $\delta^{18}O$ values and $\delta^{13}C$ values between –1 and –7‰ PDB are typical for calcite precipitating under hydrothermal conditions or precipitation from glacial waters (e.g. /Tullborg et al. 1999, Hoefs 2004/). At Forsmark, however, the hydrothermal parageneses with coeval formation of adularia, prehnite and laumontite clearly implies a hydrothermal origin to this calcite. The trend toward enriched $\delta^{18}O$ values in many calcites is probably due to an 'oxygen shift' where interaction with the wall rock increases the $\delta^{18}O$ value of the fluid (e.g. /Drever 1997/) which is subsequently inherited by the calcite during precipitation. Intensive water-rock interaction is supported by the observed wall rock alteration associated with precipitation of the hydrothermal calcite. No significant correlation between $\delta^{18}O$ in calcite and the temperature stability of coexisting minerals (adularia, prehnite or laumontite) can be seen. This is probably due to the influence from the wall rock on the $\delta^{18}O$ value in Generation 2 calcites which predominates over a possible temperature dependent fractionation of oxygen isotopes during the calcite precipitation. Different intensities of water/rock interaction in different fractures give high spatial variations in the $\delta^{18}O$ value in the groundwater later inherited by the precipitated calcite. This is in agreement with the variation in $^{87}Sr/^{86}Sr$ ratios (0.707 to 0.713 in all but one sample of 0.715) (Figure 6-10). The wall rock alteration adjacent to fractures with Generation 2 minerals is characterised by almost complete saussuritisation of plagioclase releasing calcium and strontium from the plagioclase. This would have a significant impact on the strontium isotopic composition of the fluid; on the other hand the wall rock alteration also includes the formation of chlorite and breakdown of biotite, so the strontium isotope signature of the hydrothermal fluid probably contained radiogenic strontium as well.

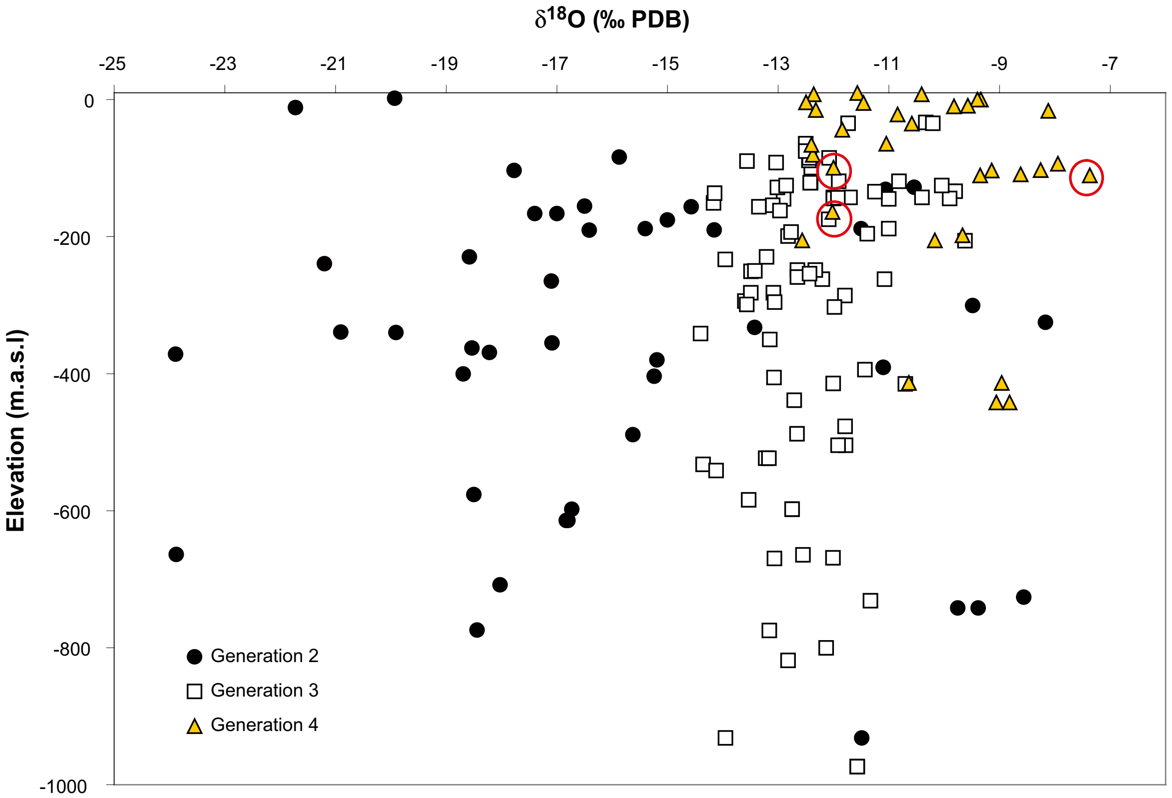


Figure 6-9. *$\delta^{18}O$ versus depth (elevation) in calcite. Analytical errors are denoted by the size of the symbols. Three generation 4 calcites with $^{87}Sr/^{86}Sr$ overlapping with present groundwaters are marked with red circles.*

Palaeozoic Generation 3 calcite

Palaeozoic generation 3 calcite shows a narrower span in $\delta^{18}O$ values (–9.6 and –14.4‰ (PDB) compared with the older generation 2 calcite. In contrast to relatively homogeneous values in $\delta^{18}O$, extreme variation in $\delta^{13}C$ values spanning from –2.4 to –53.1‰ PDB (Figure 6-8) is shown. The variations seen in the $\delta^{18}O$ values could be due to different temperatures during precipitation and/or variation in the isotopic composition of the fluid. A moderate interaction with the wall rock is also possible. A few generation 3 calcites show $\delta^{18}O$ values in equilibrium with the present groundwater at ambient temperatures. However, the composition of the formation fluid during the Palaeozoic was most likely very different from the present and, furthermore, temperature indicators (e.g. fluid inclusions) indicate formation temperatures well above the present. Therefore, comparison between generation 3 calcite and the present groundwater is not valid. $\delta^{13}C$ values in calcite between –7 and –30‰ PDB indicate an organic influence on the fluid /cf. Tullborg et al. 1999, Wallin and Peterman 1999/ which is in agreement with the proposed downward penetration of fluids from an organic rich sedimentary cover as proposed by the presence of asphaltite in the upper parts of the bedrock /Sandström et al. 2006a/. More extreme $\delta^{13}C$ values (<–30‰ PDB) are due to microbial oxidation of organic matter under in situ non-equilibrium conditions resulting in extreme depletion of ^{13}C in the produced HCO_3^-/CO_2 which subsequently is inherited into the precipitating calcite /Pedersen et al. 1997, Budai et al. 2002/. Generation 3 calcites can also be distinguished from older calcite by their higher $^{87}Sr/^{86}Sr$ values (Figure 6-10).

Homogenisation temperatures (T_H) obtained from fluid inclusions in Generation 3 calcite separate into two groups; T_H 161–186°C and T_H 64–109°C /Sandström et al. 2008/. Fluid inclusions with lower T_H are found in calcites that have grown on quartz coatings and are shifted toward more saline composition (12–19 wt% CaCl eq). From a palaeohydrogeological perspective it is of interest to note the strong evidence of a highly saline organic rich fluid present in the crystalline rock aquifer during this time period (i.e. the Palaeozoic).

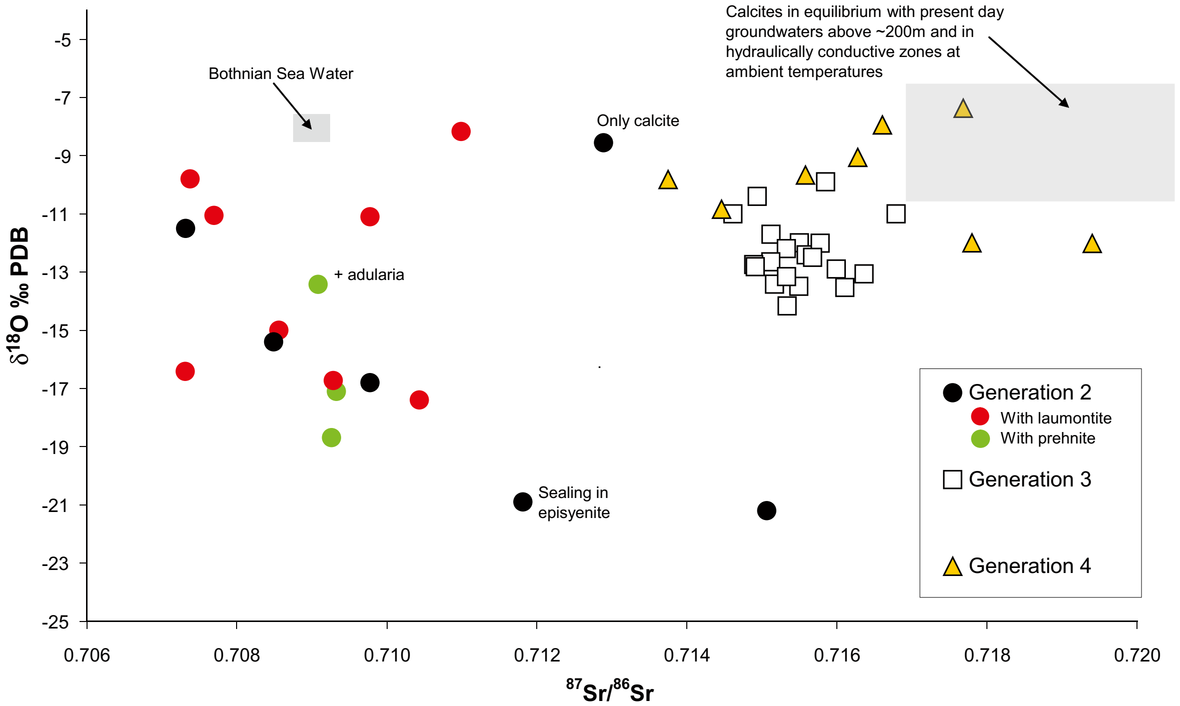


Figure 6-10. *^{87}Sr/^{86}Sr ratio versus δ^{18}O (PDB) in fracture filling calcite. Cogenetic minerals for Generation 2 calcites are marked by the colour of the dots. Notice the overlap in ^{87}Sr/^{86}Sr ratios in calcite cogenetic with prehnite and laumontite. The isotopic composition of Bothnian Sea Water and groundwaters down to around 200 m depth and in hydraulically conductive zones, is presented in /SKB 2007/. Brackish marine groundwaters (–10 to –8.5‰ SMOW) dominate in the conductive zones and Fresh meteoric water (–12 to –10.5‰ SMOW) in the upper 100 m. For calculation of δ^{18}O in calcite at equilibrium with these waters, the fractionation formula by /O'Neil et al. 1969/ has been applied at a temperature of around 7°C.*

The youngest calcites (Generation 4)

Generation 4 calcites overlap in both δ^{13}C and δ^{18}O values with the Palaeozoic (generation 3) calcite, although a shift towards higher values can be seen in both δ^{13}C and δ^{18}O values. Some of this overlap could be due to overgrowth of younger calcite on older Palaeozoic calcite, but a large part of the variation can be assumed to correspond to precipitations from very different groundwaters. Generation 4 calcite is expected to represent calcites formed mainly during the Cenozoic. During this period marine-brackish to meteoric waters have recharged during temperate and cool climate conditions and these may have taken part in the calcite dissolution/precipitation processes. Calcites with δ^{18}O values between –11 and –7‰ PDB may have precipitated from waters similar to the present groundwater in the upper 200 m (Figure 6-9). Calcites with lower δ^{18}O could have been precipitated from a groundwater influenced by a larger glacial component. A few calcites display positive δ^{13}C values, possibly due to in situ microbial activity involving CH_4-CO_2 fractionation processes. Eight samples, representing the younger generation 4 calcites, were possible to analyse for ^{87}Sr/^{86}Sr (Table 6-2) and of these, five calcite samples show values similar to those in the Palaeozoic calcites, although three samples show more radiogenic signatures. Only one calcite has been identified at equilibrium with both δ^{18}O and ^{87}Sr/^{86}Sr in the present groundwater at ambient temperatures. Two calcites have been identified which have ^{87}Sr/^{86}Sr ratios overlapping with the present groundwaters but are not in equilibrium with the δ^{18}O values measured in groundwaters above 200 m. These calcites could be recently precipitated during a cooler climate, but could also have precipitated during older periods when the groundwater had a similar composition. Given these observations, it is suggested that precipitation of calcite at present (if any) is very small.

Table 6-2. Compilation of Ca/Sr (by weight) and $^{87}Sr/^{86}Sr$ ratios in different generations of calcite, rock types and groundwaters at the Forsmark site. Rock data have been extracted from Sicada as the data file p_geochemistry.xls, and water chemistry has been obtained from Sicada. Rock type 101057 is the dominant rock type within the Forsmark target area and the host of the majority of the sampled fractures.

Samples	Ca/Sr (by weight)	$^{87}Sr/^{86}Sr$
Generation 2 calcite	1,258 – 2,247	0.7073 – 0.7151
Generation 3 calcite	6,828 – 19,545	0.7146 – 0.7168
Generation 4 calcite	n.a.	0.7137 – 0.7194
Granite (to granodiorite) (rock type 101057)	72 – 125	0.7525 – 0.8059 (n=3)
Granodiorite, tonalite and granite (rock type 101051)	56 – 171	0.7116 (n=1)
Surface waters	70 – 1,106	0.7121 – 0.7381
Groundwater	81 – 185	0.7169 – 0.7244
Baltic Sea Water	63 – 74	0.7094 – 0.7095 (0.7107*)

* Outlier

The $^{87}Sr/^{86}Sr$ ratio of Baltic Sea water is also marked in Figure 6-10. Infiltrating waters, however, quickly change their $^{87}Sr/^{86}Sr$ ratio in response, for example, to water-mineral interaction along the flow path when entering a fracture system in crystalline bedrock. This may be due to ion exchange with clay minerals /Peterman and Wallin 1999/ or Al-silicate alteration. As shown in Figure 6-9, Generation 4 calcites are generally found in the upper 200 m of the bedrock except for some samples selected from 400 m depth in deformation zones ZFMA2 and ZFMA7.

6.5.3 Changes in pH and redox conditions

Different mineralogical and geochemical indicators, such as the distribution of Fe(II)/Fe(III) minerals and behaviour of redox sensitive elements such as cerium and uranium, can be studied in order to reveal the existence of possible redox front development, for example, in the near-surface bedrock environment (cf. tentative sketch in Figure 6-11). A major problem encountered at the Forsmark site is that most of the core drilling did not start at the bedrock surface and the amount of data from the uppermost part of the bedrock is therefore insufficient. Furthermore, the uppermost hundred metres of the bedrock is characterised by subhorizontal to gently dipping, highly transmissive fractures and sheet joints (i.e. the shallow bedrock aquifer), which creates a strong horizontal flow and a typical vertically-propagating redox front is not likely occurring during present conditions.

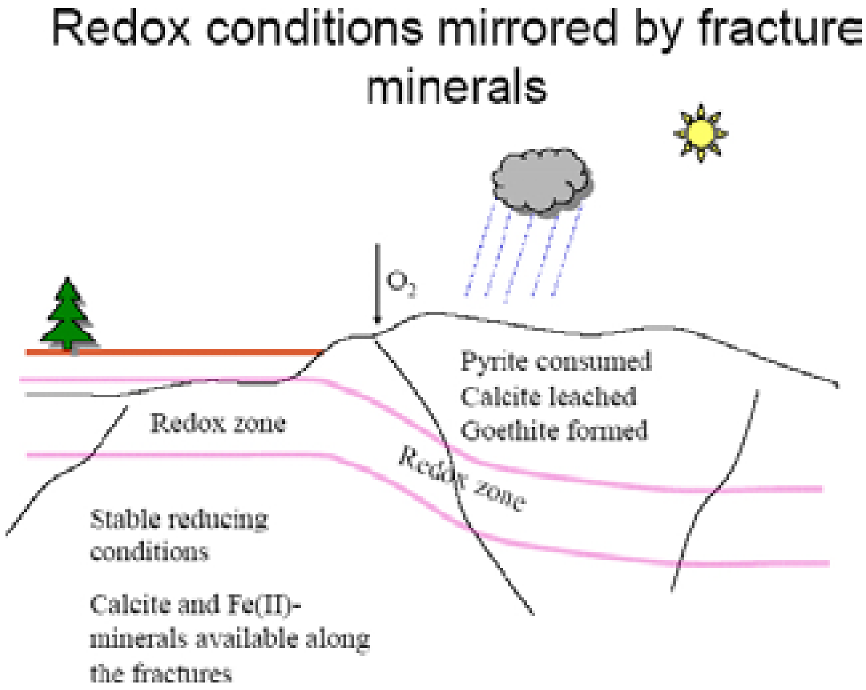


Figure 6-11. *Schematic figure of variations in fracture mineralogy demarcating the position of the redox zone. The figure is based on redox indicators summarised in /Tullborg et al. 2008/.*

Nevertheless, based on the Fe(II)/Fe(III) ,Ce and U redox indicators which are useful in order to deduce changes in redox conditions (Figure 6-12), the following observations of redox conditions can be made in the candidate area /Sandström et al. 2008 and references therein/:

- The two earliest events of fracture mineralisation (generation 1 and 2 of Proterozoic age) are characterised by the presence of oxidised Fe^{3+} (in haematite) and a number of Ce-anomalies in fracture coatings. These observations are interpreted as indicative of oxidising conditions coeval with their formation. On the other hand, chlorite with a significant Fe^{2+} content is also part of the generation 1 and 2 parageneses, suggesting variable redox conditions both in time and space. Related to these two fracture generations are also hydrothermal alteration/oxidation of the wall rock adjacent to the fractures. The major mineralogical changes in these altered rims (which normally extend a few centimetres into the wall rock) are almost complete saussuritisation of plagioclase, chloritisation of biotite and to some extent haematisation of magnetite. The overall increase in Fe^{3+}/Fe(tot) is small (approximately 10%).
- Generation 3 (Palaeozoic age) is characterised by reducing conditions as indicated by pyrite precipitation and also supported by the organic influence on the formation fluid during this period. Well-preserved pyrite crystals of Palaeozoic origin (generation 3) in many of the transmissive fractures suggest that reducing conditions have prevailed in large parts of the fracture system since this period.
- The presence of goethite (FeOOH) (generation 4) in some hydraulically-conductive fractures and fracture zones (mainly within the gently dipping deformation zone ZFMA2) in the uppermost part of the bedrock, indicates circulation of oxidising fluids during some period in the past (potentially Quaternary). This is also supported by a high oxidation factor (Fe^{3+}/Fe(tot) determined from Mössbauer spectra), seen in a few fracture coatings from the upper 100–200 m. However, the presence of pyrite in the same zones suggests that the circulation of oxidising fluids has been concentrated along channels in which different redox micro-environments may have been formed.

- Uranium-rich phases are present in some of the fracture coatings although to date only one small grain of pitchblende has been identified /Sandström et al. 2008/. The origin of these phases is largely unknown but it can be concluded that uranium has been circulating throughout the geological history of the site. For example, some of the pegmatites show slightly enhanced uranium values (a maximum value of 62 ppm is indicated by gamma spectrometric data /Stephens et al. 2007/). Even more importantly, there is evidence of redistribution and deposition of uranium irregularly along permeable structures during the Proterozoic /Welin 1964/. Moreover, during the Palaeozoic, potentially U-rich alum shales covered the area and these may have made a contribution of uranium to the system. Of special interest for understanding the present groundwater/mineral systems is the potentially late (Quaternary) redistribution of uranium. The use of U-series decay isotope analyses (USD) on groundwaters and fracture coatings concluded that part of this uranium has been mobile during the last 1 Ma /Sandström et al. 2008/. Mobilisation, as well as redeposition of uranium in the upper part of the bedrock (150 m) is indicated. This is ascribed to the transition from near-surface oxidising conditions to more stable reducing conditions at depth. However, some of the deeper samples show similar behaviour which may be explained by the presence of an easily dissolvable and partly oxidised uranium-phase, i.e. possibly altered pitchblende in type. Mobilisation and redeposition of this phase does not mean that oxidising water has penetrated to this depth. Instead, it suggests that mildly reducing groundwaters with sufficient HCO_3 (>30 mg/L) are capable of keeping U(VI) mobile, resulting in variable accumulations occurring within the fracture zones to maximum depths of around 600 m (cf. section 5.3).
- Any potential build up of reducing capacity in the fracture minerals during recent periods of reducing groundwater conditions is difficult to estimate. Processes that may contribute to increase the redox capacity include the production of Fe^{2+} and Mn^{2+} that may either precipitate (e.g. coprecipitation in calcite) or be sorbed on mineral surfaces due to ion exchange. In addition, iron sulphides may be formed due to bacterial activity of sulphate reducers. However, it can be concluded that the amounts of recent (Quaternary) minerals formed is very small.
- No significant decrease in the frequency of calcite coated fractures in the uppermost part of the bedrock (except for the uppermost metres that have not been possible to study in detail) can be seen, indicating that no extensive calcite leaching has occured in response to Quaternary glaciation/deglaciation events.

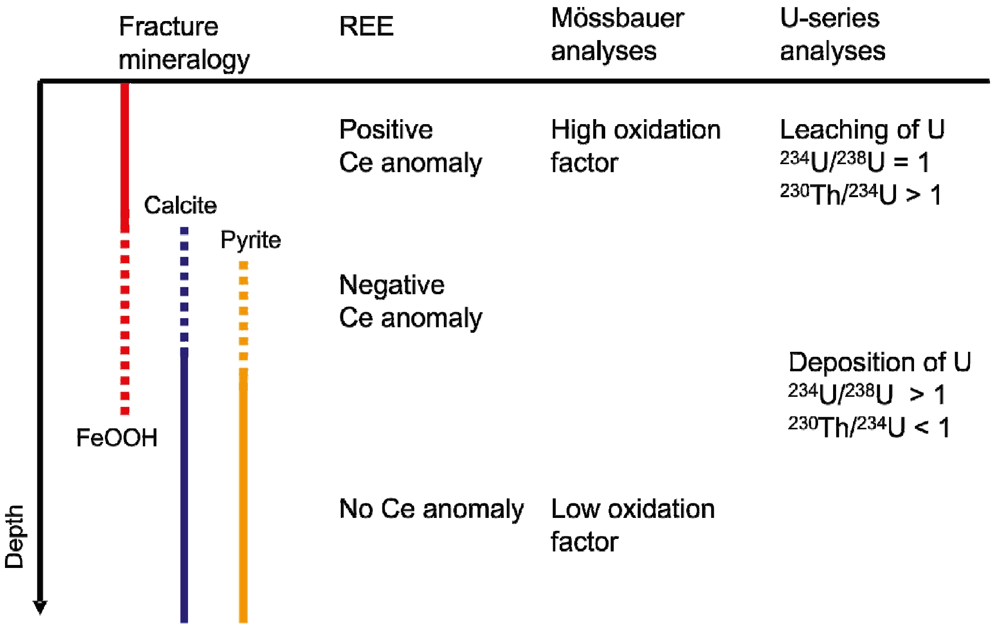


***Figure 6-12.** Schematic depth profile highlighting some of the redox indicators used for identifying the redox zone. FeOOH=goethite. The figure is based on redox indicators summarised in /Tullborg et al. 2008/.*

6.6 Groundwater residence time

A key factor in understanding past and present groundwater evolution in the Forsmark area is to constrain the average residence time for each of the major groundwater types. This can be approached qualitatively in terms of the major and trace element compositions of the groundwaters, i.e. based on aspects of water-rock reaction kinetics. Following the basic thermodynamic rules each groundwater will try to achieve chemical and isotopic equilibrium with the surrounding rock at any place along its flow path by dissolving minerals. Considering different groundwaters that evolve in a similar geologic environment such as the granitic rocks at Forsmark, a greater groundwater mineralisation can be indicative for a greater residence time. As for the radionuclides, mixing of different water bodies will complicate such considerations, but mixing can be identified by utilising isotope studies (e.g. stable isotopes of ^{2}H, δ^{18}O, ^{11}B/^{10}B, ^{37}Cl, δ^{13}C, δ^{34}S and ^{86}Sr/^{87}Sr). On a more quantitative level, because of their known half-life decay character, the radioactive isotopes of ^{3}H, ^{14}C, ^{4}He and ^{36}Cl are used in the hydrochemical studies.

Using both qualitative and quantitative approaches (cf. section 5.9), and from general hydrogeochemical and hydrogeological considerations, the Forsmark site can be subdivided into three major groundwater groups of different age ranges which can be related to approximate depth intervals. Fortuitously the choice of isotopes available for dating purposes within the hydrochemical programme coincided with the age ranges of the three groundwater types, and in two cases more than one isotope could be used. The main conclusions reached are:

- Recent to young fresh groundwaters, some showing signs of mixing, characterise the upper approximately 100–150 m of the bedrock. At these depths, because the hydraulic system is more dynamic, climatic changes have resulted in the cyclic introduction and flushing out of different groundwater types over tens of thousands of years such that residence times for individual groundwater types seem relatively short, i.e. probably some hundreds to a few thousand years. This is borne out by tritium and ^{14}C which indicate that near-surface groundwaters have short residence times in the order of only a few decades to a few hundred years. This is in agreement with palaeohydrogeological evidence which indicates emergence from the Baltic Sea occurring at Forsmark (and therefore subsequently facilitating meteoric water recharge) some 2,500 years ago.
- Older groundwaters of a distinct Littorina type occur from approximately 150 m to depths of around 300–600 m (depending on the location and fracture transmissivity). The radiocarbon analyses support a postglacial origin for the brackish marine (Littorina) groundwater, and ^{14}C at 45–53 pmC in the organic phase is in accordance with palaeohydrogeological estimations which suggest an age of approximately 5,000–6,000 years covering the period of maximum salinity during the Littorina stage (4500–3000 BC). Because of the relatively short residence time, these groundwaters have not undergone major water/rock alteration and most observed changes are due to mixing with other groundwater sources with the addition of microbial modifications, silicate weathering and ion exchange.
- Significantly older groundwaters, found at depths greater than around 300–600 m (depending on the location and transmissivity) to around 1,000 m, are characterised initially by brackish non-marine groundwaters which become successively more mineralised with increasing depth (to saline in type) by water/rock interaction, mixing with (unknown) deep saline water, and exchange with the rock matrix porewater. Hydraulic conditions at these depths indicate decreasing goundwater flow to stagnant conditions and suggest residence times that appear to be considerable. From ^{36}Cl and ^{4}He systematics, the residence time of the brackish to saline non-marine groundwaters can be shown to extend back to at least 1.5 Ma.
- No highly saline groundwaters (> 20,000 mg/L Cl) have been sampled at Forsmark, but as indicated by the porewaters /Waber et al. 2008/ there is a high probability that they exist at greater depths (e.g. KLX02 in the Laxemar subarea) and are at least as old as the shallower brackish non-marine groundwaters.

6.7 Conceptualisation from before the last deglaciation to the present day

For understanding the evolution of groundwaters in the Forsmark area it is evident that to consider only the post glacial time can be seriously misleading. Porewater analyses and groundwater samples from relatively tight and isolated bedrock in the target area of the candidate site show compositions not significantly influenced by either glacial meltwater (of unknown age) or recent brackish marine water (i.e. Littorina Sea or Baltic Sea origin).

In all Nordic sites investigated for groundwater chemistry, increasing salinity with depth is encountered. The form and gradient of the salinity profiles, however, vary considerably as a consequence of different hydraulic properties and late geological evolution (mainly Quaternary and especially Holocene). In addition, areas close to the Baltic Sea have undergone repeated transgressions and regressions of marine and fresh water during the glacial cycles.

Down to approximately 300–600 m (depending on location in the footwall or hanging wall respectively) brackish marine groundwaters occur, but at greater depths clear marine signatures are more difficult to detect although their apparent absence may have been influenced by mixing and reactions. Brackish non-marine groundwaters (5,000–10,000 mg/L Cl), usually found from 300–700 m depth and deeper, are significantly influenced by mixing, reactions and interaction with pore fluids in the rock matrix (by diffusion processes). Furthermore, portions of these waters have resided in the bedrock for very long periods of time, for example, long enough to change the $\delta^{18}O$ and $\delta^{2}H$ ratios causing deviations from the Global Meteoric Water Line (cf. section 5.10, Figure 5-61). At still greater depth (>1,500 m) highly saline water of brine character and unknown age and origin can be expected.

In the context of geological time scales, fluid inclusions in calcite of Palaeozoic origin show the presence of very saline (around 20 wt%) mainly Ca-Cl fluids /Sandström et al. 2008/. It can be assumed, therefore, that during the Late Palaeozoic when several kilometres of marine and terrestrial sediments covered the Precambrian Shield area of SE Sweden, brine solutions were formed allowing very highly saline waters to slowly penetrate and saturate both the fractures and interconnected pore spaces in the underlying crystalline bedrock (Figure 6-13).

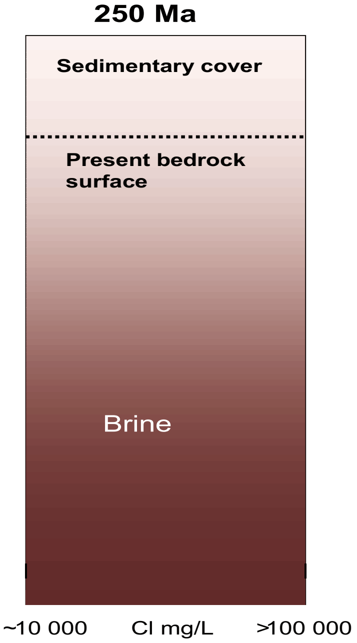


Figure 6-13. A simplified sketch of the groundwater situation during the Late Palaeozoic when the Forsmark area was covered by large thicknesses of marine and terrestrial sediments /Cederbom et al. 2000/.

Subsequent erosion slowly reduced this sedimentary cover until, in the Late Tertiary, the present Precambrian Shield bedrock was exposed once again /Lidmar-Bergström 1996/. This re-exposure of the crystalline rock, in particular the effect of subsequent glaciations and interglaciations during the Quaternary, has resulted in a flushing out and dilution of the brine in the upper 1,000 m (or more) of the bedrock. In addition, close to the Baltic Sea coast repeated transgressions and regressions resulting from isostatic rebound following ice melt have caused oscillations between marine and meteoric groundwater environments. This means that several generations of meteoric waters from cold and temperate periods, and also Baltic Sea waters from different evolution states of the Baltic region prior to the last Weichselian glaciations, have influenced the area, and portions of these different waters are still present today.

Figure 6-14a shows a tentative distribution of groundwater types and salinity gradients in the Forsmark area before the intrusion of the last deglaciation meltwater just prior to the Holocene. From present Quaternary evidence, it is logical to assume that there must have been at that time old meteoric waters comprising components derived from both temperate and cold climate events. These would have mixed gradually with deeper, more saline groundwaters, probably of mixed origin but without a clear residual marine signature remaining. This situation seems to be still valid for the most isolated parts in the bedrock, for example in low transmissive fractures within the footwall (i.e. fracture domain FFM01; boreholes KFM01D and KFM08D). In the more hydraulically conductive gently dipping deformation zones of the hanging wall, however, characteristic of fracture domain FFM03, the last deglaciation meltwater was intruded to several hundreds of metres (Figure 6-14b) and more or less fresh water dominated the upper 400 to 500 m in the most conductive zones.

During the subsequent Littorina Sea stage (Figure 6-14c), the Forsmark area was covered by brackish marine water assumed to be at around 6,500 mg/L Cl /Pitkänen et al. 1999, 2004/. This maximum salinity (twice the present salinity of the Baltic Sea) lasted between 4500 and 3000 BC. Due to density intrusion the Littorina Sea water entered the deformation zones and fractures and mixed with the previously resident fresh water of glacial and old meteoric character (Figure 6-14c).

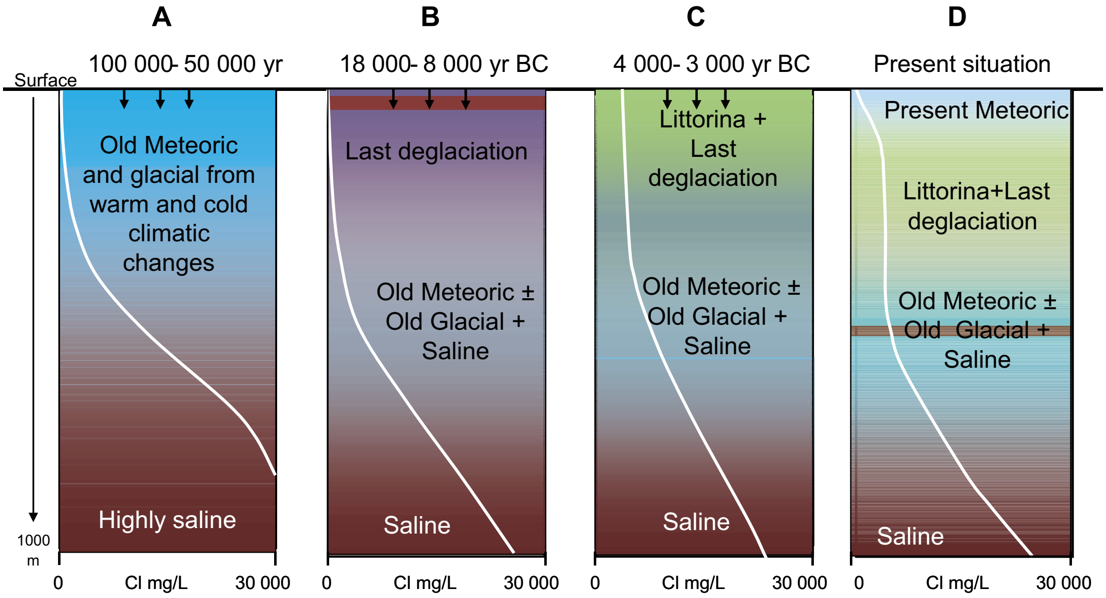


Figure 6-14. Sketch showing tentative salinities and groundwater-type distributions versus depth for the transmissive zones at Forsmark. From left to right: a) situation prior to the last deglaciation, b) intrusion of the last deglaciation meltwater, c) Littorina Sea water penetration caused by density intrusion (or turnover), and d) present day situation.

The present situation is shown in Figure 6-14d, which illustrates the flushing out of the brackish marine groundwater (i.e. dominantly Littorina Sea water) in the upper part of the bedrock by recharged meteoric groundwaters particularly during the last 1,000 years. This flushing process commenced during land rise above sea level with the establishment of hydraulic gradients and is continuing to the present day. Today, the most recent glacial water can no longer be identified as a major component in the bedrock, but rather constituting a minor part in the brackish marine (Littorina Sea type) water and older brackish non-marine groundwaters due to mixing.

The above description is valid generally for areas in the Forsmark bedrock where first the last deglaciation meltwater and then later the brackish marine (Littorina Sea) water have been introduced; the Littorina Sea water has only been able to intrude (by density intrusion) were fresh water with a large component of last deglaciation meltwater had previously filled the fractures. Therefore two different systems have developed in the Forsmark area:

- The highly transmissive, gently dipping deformation zones of the hanging wall bedrock, and the open, transmissive fractures and sheet joints in the upper footwall bedrock (i.e. fracture domain FFM02), where all water types: a) saline, b) brackish non-marine (i.e. Old Meteoric ± Old Glacial + Saline), c) last deglaciation, d) brackish marine (Littorina), and e) presently altered Meteoric, can be found to have interacted to various degrees.
- The footwall target area (i.e. fracture domain FFM01), characterised by horizontal/sub-horizontal low transmissive single fractures dominated by brackish to saline non-marine groundwaters.

6.8 Groundwater end members: Their use for modelling purposes and the problem with identification

6.8.1 “Representative” end members

The various groundwater end members used, for example, to derive modelled mixing proportions /e.g. Laaksoharju et al. 1999, Gurban 2008/ are based on Palaeohydrogeochemical considerations. The chosen end members to represent the Forsmark groundwater system are Deep Saline, Glacial, Littorina and Altered Meteoric. Several of these end members, however, when intruded initially along the bedrock fracture and deformation zones (e.g. comprising brackish marine and meteoric waters from warm and cold climate cycles) will undergo changes in composition with time and soon have their original chemical signatures modified, eventually becoming difficult to distinguish properly. It is only in the upper part of the bedrock that a pure end member can exist, and probably only for a very short period of geological time. As soon as the new end member begins to migrate through the bedrock (or even the soil cover) it will change composition by: a) mixing with the different waters that already characterise the bedrock, b) reactions of varying importance (e.g. ion-exchange; microbially mediated reactions etc), and c) diffusion either into or from the rock matrix depending on existing concentration gradients. In such a hydraulically-active system, high to moderate transmissive bedrock will always be in a transient state and will always reflect some kind of a salinity gradient towards depth. In other words, the chances of present-day sampling of a pure end member in the bedrock are virtually zero. They may be trapped in pockets or lenses close to the surface, but usually this is the least likely location because of high fracture frequency and high transmissivity. Therefore, the present groundwater end member types identified (excluding Deep Saline) really should be preceded by ‘Altered’ in common with ‘Altered Meteoric’.

For modelling purpose, however, and to avoid confusion, the ‘pure’ or ‘original’ end member compositions are usually used, simply because the altered end members can be difficult to define, for example, which Altered Littorina or which Altered Glacial compositions should be used?

6.8.2 Alteration of end members

Last deglaciation meltwater

Considering the most recent glacial event prior to the Holocene, the last deglaciation meltwater (i.e. the Glacial end member) enters the bedrock under high hydraulic head pressures and mixes/reacts with the altered Old Meteoric ± Old Glacial + Saline water (termed *'Brackish to Saline Non-marine'*), which itself varies in its chemical and isotope composition with depth due to an increasing saline groundwater input. In addition, concentration gradients are initiated between the rock matrix porewater and fracture groundwater. This diffusion gradient probably extends from the matrix towards the more dilute water in the fractures, assuming at least that the porewater could be similar in salinity to the brackish non-marine composition if near steady-state conditions had been achieved up to the last deglaciation. These diffusion changes, therefore, will alter the salinity of last deglaciation meltwater in the fractures and also change its $\delta^{18}O$ signature to higher values (e.g. the porewaters normally have enriched $\delta^{18}O$ values and also the brackish non-marine type will have higher $\delta^{18}O$ values than the recently introduced last deglaciation meltwater).

Pre-Littorina

Prior to the Littorina Sea transgression (cf. Figure 6-14b) there will exist, therefore, in the upper bedrock, a mixed water of brackish non-marine type, potentially with an additional saline input from along diffusion gradients at depth (i.e. another source of enriched $\delta^{18}O$). During the Ancylus Lake stage no hydraulic gradient will exist and therefore mixing between Ancylus water and groundwaters in the upper bedrock will not occur. In terms of reactions at the lake bottom, the Ancylus water may increase in TDS due to water/rock interaction processes and possibly also microbial reactions. In addition, depending on the upper bedrock water composition there may be some interaction between the bedrock and the lake bottom if concentration gradients exist. This is, however, probably a minor influence.

Littorina Sea transgression

The next stage is the Littorina Sea transgression event (cf. Figure 6-14c) which is assumed to be much more saline than the relict mixed water in the upper 500–600 m bedrock mainly derived from the last deglaciation event plus subsequent meteoric input. This resulted in a density intrusion. As described for the last deglaciation meltwater component, the Littorina Sea will enter a mixed water environment characterised by not only an increased salinity gradient with depth, but also a significant gradient in $\delta^{18}O$ composition. Figure 6-15 suggests a depleted $\delta^{18}O$ signature of around –20‰ SMOW close to the surface reflecting a mixture of last deglaciation and post-glacial fresh meteoric recharge waters. With increasing depth, accompanied by an increase in the brackish non-marine component and a decrease of last deglaciation /fresh meteoric waters, $\delta^{18}O$ becomes increasingly enriched; a trend which continues down to the dominant underlying brackish non-marine groundwaters where $\delta^{18}O$ is around –12‰ SMOW. The Littorina also will undergo change by mixing, reaction and porewater diffusion. With respect to mixing, any Littorina interaction with the resident brackish non-marine type groundwater will further enrich the $\delta^{18}O$ signature.

This density intrusion terminated at around 600 m along the highly transmissive, gently dipping deformation zones in the hanging wall bedrock (and to around 300 m in association with the low transmissive, single open fractures in the footwall bedrock, i.e. fracture domain FFM01), where the salinity of the resident brackish non-marine type groundwater equalled or exceeded that of the incoming altered Littorina seawater member, i.e. at around 6,000 mg/L Cl /Pitkänen et al. 1999, 2004/.

With respect to pre-Littorina rock matrix diffusion, the porewater in the upper bedrock (i.e. 0–300 m or 0–600 m depending on location) will be less saline if it is assumed that close to steady-state conditions had been established between the porewater in the rock matrixand the mainly fresh water/brackish non-marine groundwater mixture resident in the fractures (Figure 6-15). During intrusion of the higher saline Littorina Sea water the concentration gradients will be active from the fractures into the rock matrix, thus lowering the overall salinity of the Littorina groundwater to levels of around 5,500 mg/L Cl measured today. This might help to explain why no salinity signal equivalent to the assumed maximum Littorina salinity (i.e. around 6,000 mg/L Cl) has been found at Forsmark (and also Olkiluoto).

Present day

The present-day situation (cf. Figure 6-14d) now finds the altered meteoric water entering the system and mixing to various degrees with the groundwater relicts of the altered brackish marine (Littorina/Baltic, altered last deglaciation, altered brackish non-marine and deep saline, controlled by local hydraulic gradients. So, in conclusion, all plots of the Forsmark groundwaters reflect an 'altered' groundwater environment, which is to be expected, and therefore it is not anticipated to find undisturbed mixing lines between pure end members as all the end members except for 'Deep Saline'(at least in the present geological context of time and stability) are more or less hybrids.

This explains, furthermore, some of the plots involving extrapolated $\delta^{18}O$ data which consistently indicate the most depleted $\delta^{18}O$ values at around –16‰ SMOW, similar in range to those groundwaters presently resident in the bedrock.

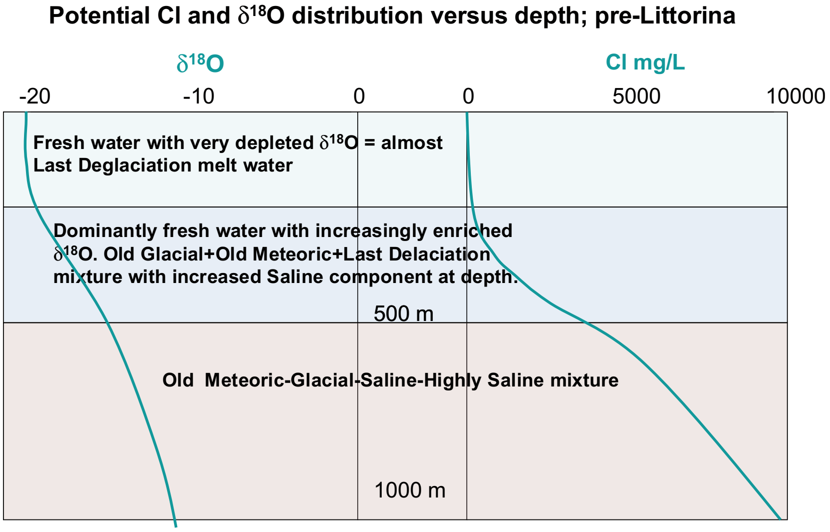


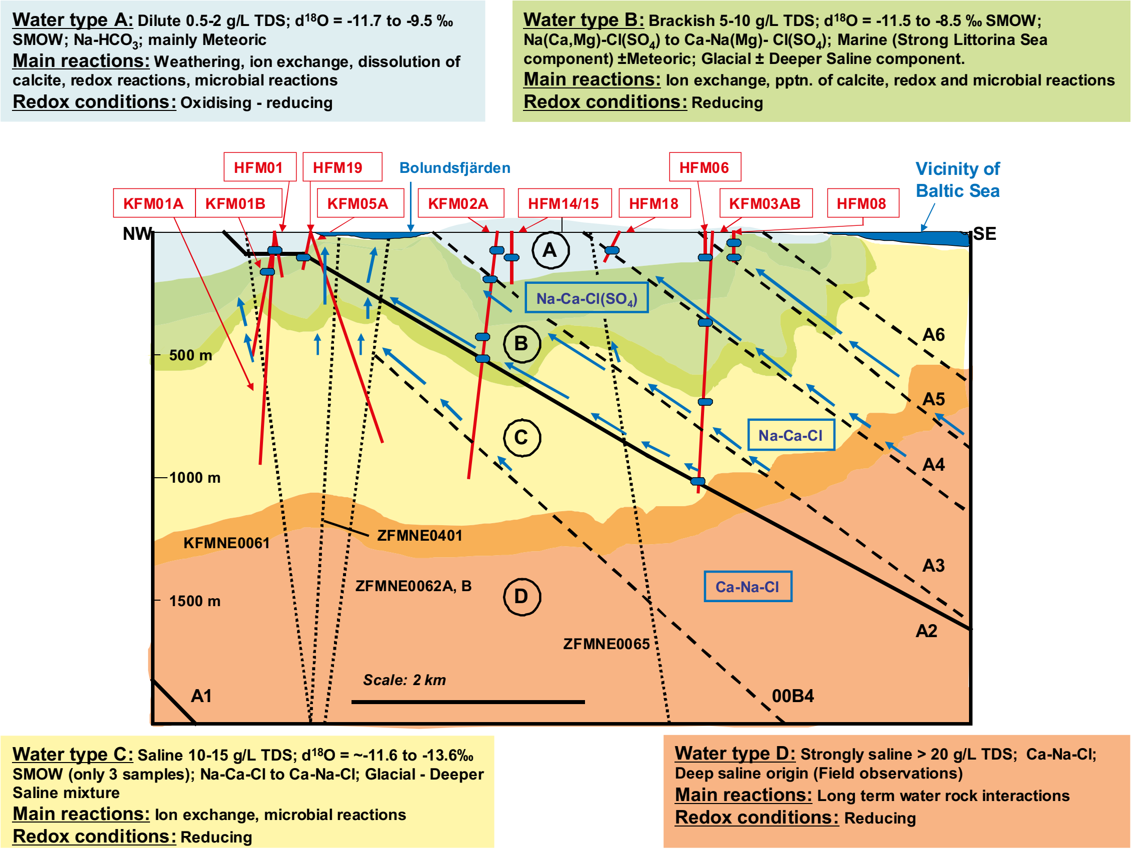
Figure 6-15. *Sketch describing possible Cl and $\delta^{18}O$ distributions versus depth in pre-Littorina time.* ***Note*** *that this situation is not representative for the lower transmissive single fracture characteristic of fracture domains FFM01 and FFM02 where last deglaciation meltwater seems not to have penetrated.*

7 Visualisation of the Forsmark area hydrogeochemical data

7.1 Background

The culmination of the Forsmark 1.1 and 1.2 visualisations, based on a WNW-ESE cutting plane through boreholes KFM03A, KFM02A and KFM01A/1B (plus extrapolation of KFM06A onto the cutting plane), is shown in Figure 7-1 /SKB 2005/. This attempts to show the spatial distribution of the four main groundwater types (A-D) and their close relationship to the geometry and hydraulics of the fracture network.

Whilst achieving some success in portraying the overall site understanding, it was still unsatisfactory from a realistic viewpoint in that it gives the impression of a geologically porous medium where groundwaters have migrated both advectively along the fracture systems and by diffusion through the rock matrix. This was largely due to a lack of data at the time; since then more groundwater data have become available, both from within and outside the candidate area confines, and rock matrix porewater studies have added a further dimension. In addition, both the geology and hydrology of the bedrock system is better understood, which in turn considerably increases the value of the hydrogeochemical data and their interpretation.


Water type A: Dilute 0.5-2 g/L TDS; d^{18}O = -11.7 to -9.5 ‰ SMOW; Na-HCO_3; mainly Meteoric
Main reactions: Weathering, ion exchange, dissolution of calcite, redox reactions, microbial reactions
Redox conditions: Oxidising - reducing

Water type B: Brackish 5-10 g/L TDS; d^{18}O = -11.5 to -8.5 ‰ SMOW; Na(Ca,Mg)-Cl(SO_4) to Ca-Na(Mg)- Cl(SO_4); Marine (Strong Littorina Sea component) ±Meteoric; Glacial ± Deeper Saline component.
Main reactions: Ion exchange, pptn. of calcite, redox and microbial reactions
Redox conditions: Reducing

Water type C: Saline 10-15 g/L TDS; d^{18}O = ~-11.6 to -13.6‰ SMOW (only 3 samples); Na-Ca-Cl to Ca-Na-Cl; Glacial - Deeper Saline mixture
Main reactions: Ion exchange, microbial reactions
Redox conditions: Reducing

Water type D: Strongly saline > 20 g/L TDS; Ca-Na-Cl; Deep saline origin (Field observations)
Main reactions: Long term water rock interactions
Redox conditions: Reducing

Figure 7-1. Forsmark 1.2 conceptual 2D model (modified from /SKB 2005/).

7.2 The Forsmark 2.3 visualisation

7.2.1 Background and construction

The approximate WNW-ESE and WSW-ENE cross-sections on which the present Forsmark 2.3 visualisations are based, are shown in relation to the geology and borehole locations and the main deformation zones (Figure 7-2). The WNW-ESE cross-section represents the standard profile through the candidate area, and has been selected to best illustrate the geology and hydrogeology. From a hydrogeochemical viewpoint, however, it proved impossible to satisfactorily reconcile in 2D the complex geology and hydrochemistry in the extended WNW part of the cross-section involving boreholes KFM07A/B and KFM09A/B (Figure 7-2). The cross-section described below is based, therefore, on a shortened version up to, and including, borehole KFM01D in the WNW, but excluding boreholes KFM07A/B and KFM09A/B. To accommodate the target volume, a separate WSW-ENE cross-section through boreholes KFM11A, KFM08A/B/D, KFM07A/B and KFM09A/B, and including the Singö deformation zones to the east, is presented and described also. The geostructural framework of the two cross-sections is based on the stage 2.2 geological model /Stephens et al. 2007/ and reproduced and described in section 2.1 (Figures 2-6 and 2-7).

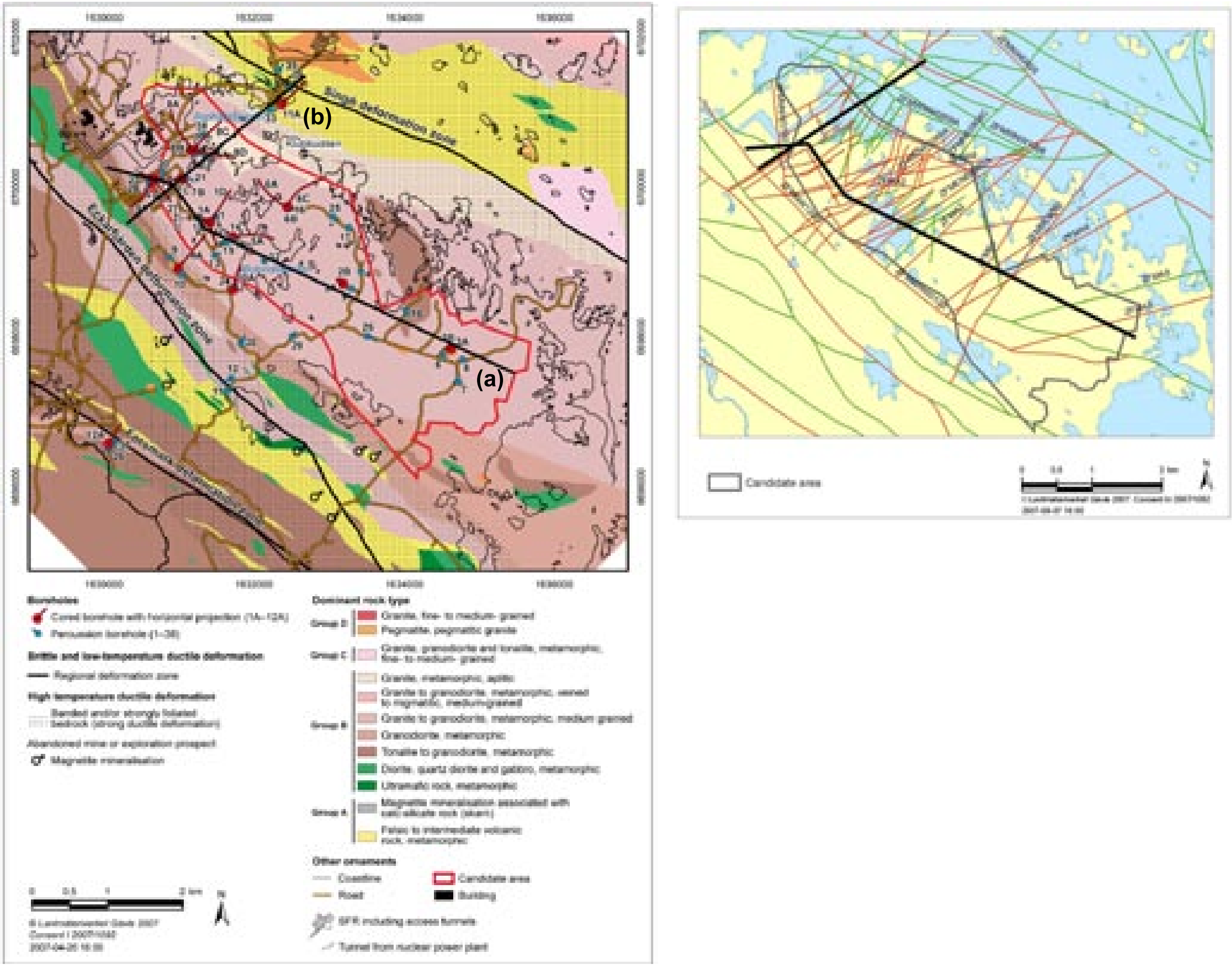


Figure 7-2. The location of the WNW-ESE and WSW-ENE cross-sections used in the visualisations: Left-hand map showing the geology and borehole locations, and right-hand map showing the main deformation zones (varieties most relevant for the visualisations are labelled) /Stephens et al. 2007/.

Based on the exploratory analysis and modelling of the hydrochemical data detailed in the preceding chapters, and considering the hydraulic parameters of the sampled water-conducting fractures and deformation zones, the various groundwater types were subdivided with respect to chlorinity (and magnesium) and elevation. These subdivisions are supported by other major ions (see below). The rock matrix between the water-conducting fractures and fracture zones, which dominates both cross-sections, has also been subdivided based on the extracted porewater chlorinity and elevation.

Using accurate but simplified versions of the modelled stage 2.2 geostructural cross-sections /Stephens et al. 2007/, the groundwater and porewater types and chlorinities were superimposed on the bedrock. To provide a more realistic visualisation of groundwaters in a fractured crystalline rock environment, i.e. to avoid giving a porous medium impression to the bedrock, the groundwater types are confined to the intersected major water-conducting fractures and deformation zones. The WNW-ESE cross-section is particularly well suited because it cuts many of the major water-conducting fractures and deformation zones (Figure 7-3). The WSW-ENE section is less suited as it cuts parallel to the major stuctures, and consequently visualisation of the groundwater types and their chlorinities can only be confined to the actual borehole sections sampled (Figure 7-4).

The subdivided porewater and fracture groundwater compositions, based on chloride concentrations, are listed and colour coded in the respective figure lengends. In both cross-sections the same chloride subdivisions are used for porewaters and groundwaters. The vertical distribution of the groundwater types is based collectively on all relevant input from the hydrogeochemical studies, integrated closely with hydrogeological interpretations (e.g. see section 2.3). The upper 300–700 m of bedrock are fairly well characterised with a correspondingly high degree of confidence. The main uncertainties are associated with the spatial lack of hydrochemical data both laterally (in particular the porewaters) and at depths greater than 700 m (particularly the fracture groundwaters), such that expert judgement has been used to extrapolate the hydrochemistry at greater depths and laterally along the extent of the cross-sections. There is, however, greater geological and hydrogeological coverage documented both laterally and to depth which has helped to extrapolate the hydrochemistry with greater confidence. Moreover, with the realisation that at depths greater than 700 m the porewater chemistries continue to increase fairly uniformly in salinity and appear to be laterally quite homogeneous, and that fracture groundwaters close to steady state conditions at equivalent depths tend to show similar chemistries, has provided additional confidence in the extrapolations made.

The porewater patterns in the upper approximately 700 m of bedrock shown in Figure 7-3 are an attempt to illustrate the effects of a dynamic flow system on the rock matrix porewater compositions derived from the samples studied. For example, this includes: a) the presence of recent, out-diffusion gradients resulting in a dilution of porewaters in the rock matrix adjacent to the gently dipping deformation zones, with an upward ‘fingering’ of older, higher porewater salinities still preserved between the deformation zones, and b) a more advanced situation, where only small residual concentrations or ‘islands’ of older more saline porewaters have been preserved in rock volumes of sufficient extent to be more slowly influenced by on-going diffusion processes between the surrounding hydraulically-active fractures or deformation zones and the rock matrix.

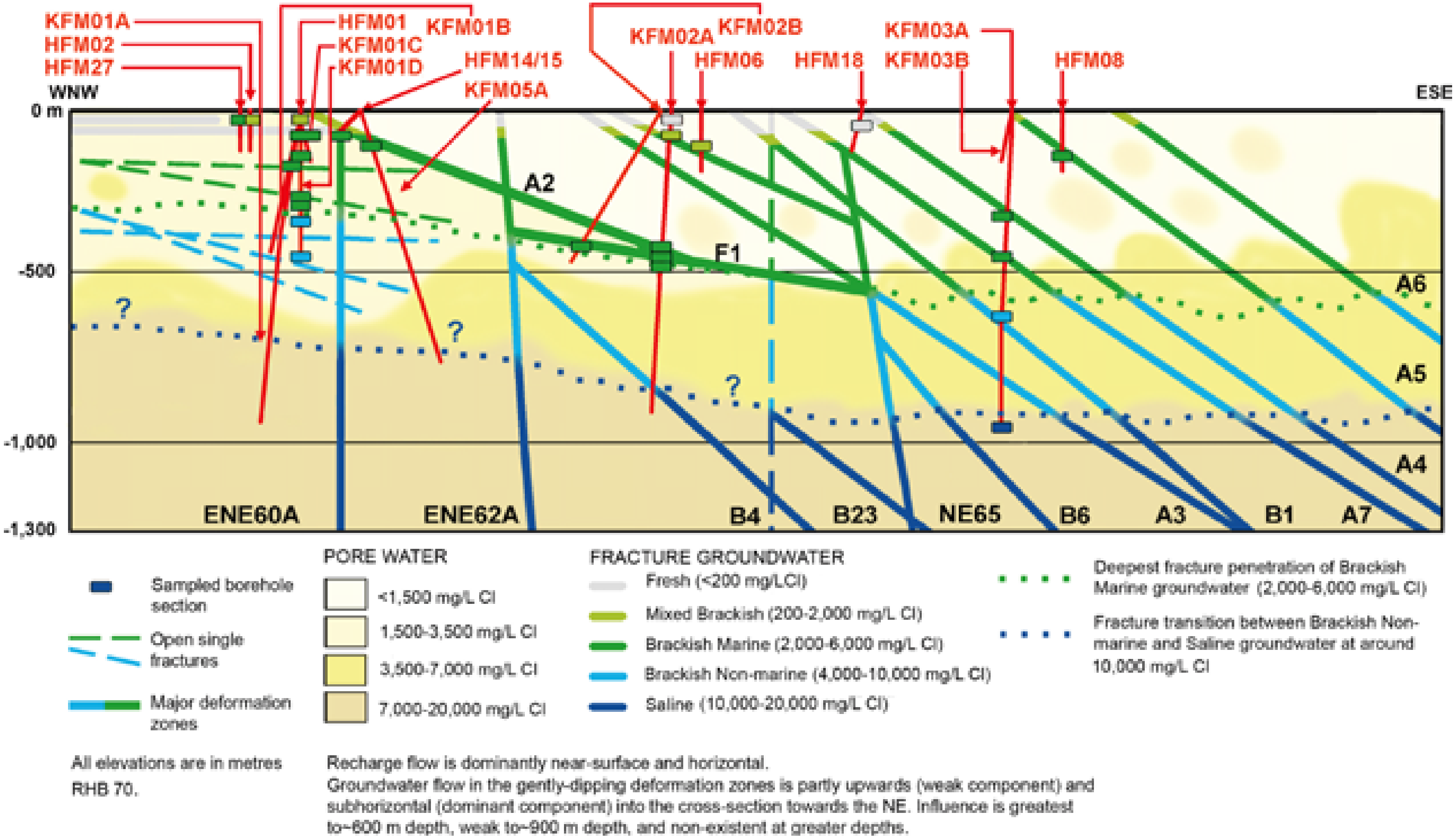


Figure 7-3. *Forsmark 2.3 visualisation of the hydrochemical data along cross-section WNW-ESE. Shown are: a) the location of the boreholes and the sections which have undergone hydrochemical sampling, b) the main fracture groundwater types which characterise the site, c) the chloride distribution with depth along the major deformation zones and minor single open fractures, and d) the chloride subdivisions of the rock matrix porewater. The groundwater flow directions are explained in the legend. The dotted lines in different colours crossing the section represent the approximate depths of penetration of (or extrapolation of) the various groundwater types along hydraulically-active deformation zones. (Cross-section length = 6,790 metres).*

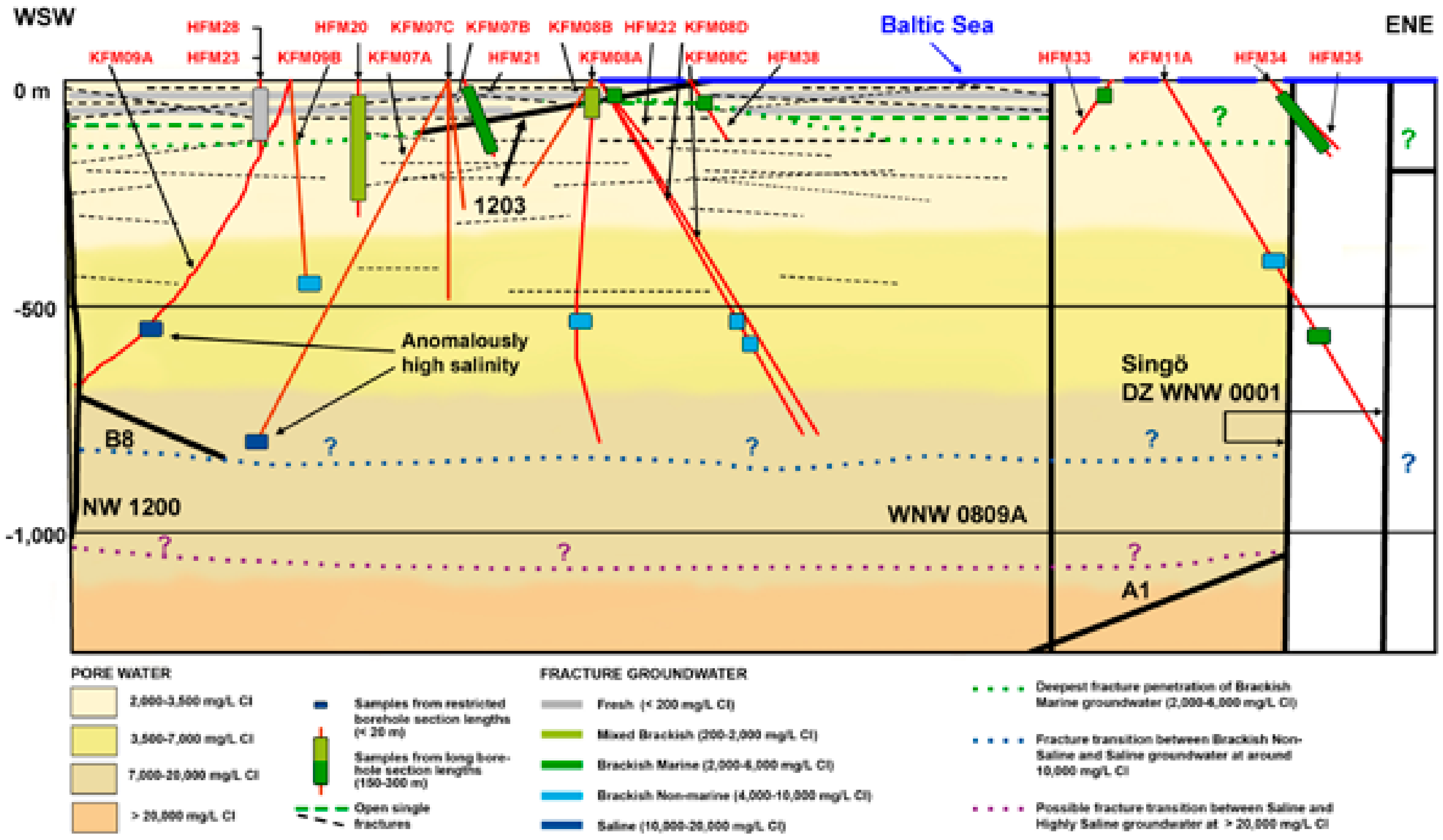


Figure 7-4. *Forsmark 2.3 visualisation of the hydrochemical data along cross-section WSW-ESE. Shown are: a) the major and minor structures, b) the location of the boreholes and the sections which have undergone hydrochemical sampling, c) the chloride distribution at each point of sampling, and d) the chloride subdivisions of the rock matrix porewater. The groundwater flow directions are explained in the legend. The dotted lines in different colours crossing the section represent the approximate depths of penetration of (or extrapolation of) the different groundwater types along hydraulically-active deformation zones. (Cross-section length = 2,975 metres).*

7.2.2 Major groundwater types

Four major groundwater types (and one mixed and one transition type) characterise the Forsmark area and these are indicated by different colour codes; see legend in Figures 7-3 and 7-4. They are:

Fresh (Light Grey)

Water type: Fresh (< 200 mg/L Cl; < 1.0 g/L TDS); mainly meteoric in origin, i.e. Na(Ca)-$HCO_3(SO_4)$-(Cl) in type (representative sample is HFM18); $\delta^{18}O = -12.3$ to -11.2‰ V-SMOW.

Main reactions: Weathering, ion exchange; possible dissolution of calcite; redox and microbial reactions.

Redox conditions: Oxidising – reducing.

Mixed Brackish (Light green)

Water type: Mixed Brackish (200–2,000 mg/L Cl; 1.0–3.5 g/L TDS); comprises a narrow horizon (approximately 50–150 m depth) distinguished by groundwaters which have been influenced by borehole activities, pumping tests and normal gradients characterised by upward and subhorizontal flow directions. These anthropogenic influences together with natural gradient mixing has occurred to varying degrees involving young meteoric water and old and modern marine waters (i.e. Littorina and/or Baltic Sea types).

Brackish Marine (Green)

Water type: Brackish Marine (2,000–6,000 mg/L Cl; 3.5–10 g/L TDS); variable Littorina Sea component (± modern Baltic Sea) + Last Deglaciation ± Saline component; Na-Ca-Cl in type (representative sample KFM02A: 490.00–518.00 m) with significant amounts of Mg and SO_4; $\delta^{18}O = -11.5$ to -8.6‰ V-SMOW (more commonly $\delta^{18}O = -10.2$ to -8.6‰ V-SMOW).

Main reactions: Water/rock interaction; ion exchange; possible precipitation of calcite; redox and microbial reactions.

Redox conditions: Marginally oxidising to reducing depending on depth of source.

Transition zone samples (not a specific groundwater type)

Transition compositions occur between the Brackish Marine and Brackish Non-marine groundwater types over varying depth intervals within a chlorinity range from 4,000–6,500 mg/L and magnesium from 25–100 mg/L. They may reflect natural and/or anthropogenic mixing during drilling activities and sampling.

Brackish Non-marine (Turquoise)

Water type: Brackish Non-marine (4,000–10,000 mg/L Cl; 8.5–16 g/L TDS); Mg < 25 mg/L; Old Meteoric ± Old Glacial ± Last Deglaciation + Saline component, i.e. Ca-Na-Cl in type (representative sample KFM01D: 568.00–575.14 m); $\delta^{18}O = -16.0$ to -10.5‰ V-SMOW.

Main reactions: Water/rock interaction; ion exchange; possible precipitation of calcite; redox and microbial reactions.

Redox conditions: Reducing.

Saline (Dark Blue)

Water type: Saline (10,000–20,000 mg/L Cl; 16–35 g/L TDS); Saline ± Old Glacial/Last Deglaciation + deeper Highly Saline component, i.e. Ca-Na-Cl in type (representative sample KFM03A: 969.50–994.50 m); $\delta^{18}O = -13.8$ to -12.9‰ V-SMOW

Main reactions: Water/rock interaction; ion exchange; microbial reactions.

Redox conditions: Reducing.

7.2.3 Distribution of groundwater types in the WNW-ESE cross-section

As discussed in section 2.1, the distribution of groundwater types illustrated in Figures 7-3 and 7-4 should be considered in terms of the hanging wall bedrock segment and the footwall bedrock segment (including fracture domains FFM01 and FFM02) which are separated by the major gently dipping deformation zones ZFMA2 and ZFMF1 in the upper approximate 600 m, and by ZFMNE65 to the maximum depth of the cutting plane (see Figure 7-3). Figures 7-5 to 7-10, addressing the distribution of chloride and magnesium with depth, are based on quality assessed data (Categories 1, 2 and 3) from water-conducting fractures/deformation zones and are not restricted only to the cutting plane borehole intersections.

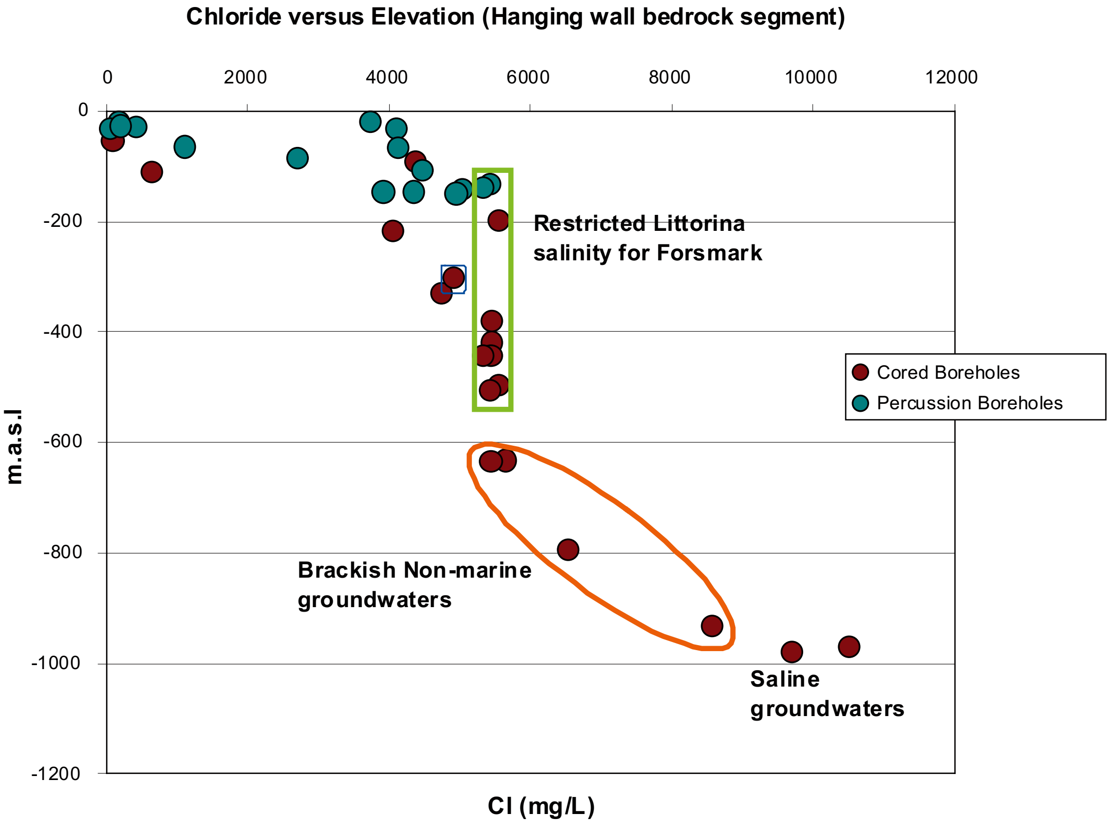


Figure 7-5. *Plot of quality assessed borehole chloride data (Categories 1–3) against elevation for the gently dipping deformation zones in the hanging wall bedrock segment showing: a) the distribution of the fresh groundwater (0–100 m), b) the strongest Brackish Marine (i.e. Littorina Sea component from 5,300–5,500 mg/L Cl) (green box) (~100–550 m), c) the transition to Brackish Non-marine (orange ringed) (~ 600 m), and d) gradual transition of (c) to Saline groundwaters (~ 600–1,000 m). Blue ringed sample represents updated F2.3 data.*

Fresh groundwaters

In the hanging wall bedrock segment, most of the gently dipping deformation zones indicate higher transmissivities in the upper 400 m of bedrock and present flow directions in the candidate area are primarily subhorizontal along these fracture planes towards the north-east with a weak upward component.

This natural hydraulic situation may explain the hydrochemical variations observed in Figure 7-5 in that the upper 100–150 m of the bedrock (particularly southeastwards towards the Baltic Sea; see Figure 7-3) the brackish marine (Littorina) type groundwaters occur higher up in the bedrock (to 50 m depth), thus preventing deeper recharge of the fresh groundwaters. In contrast, further to the north-west towards the centre of the cutting plane, the fresh groundwater horizon recharges to somewhat greater depths along some of the deformation zones (to 100–150 m), but further to the north-west were ZFMA2 is close to the surface, the brackish marine (Littorina) type groundwaters occur once again close to the bedrock surface because of the upward groundwater flow in this major deformation zone. Thus, in these gently dipping deformation zones fresh groundwater samples are few and only occur within the upper 0–100 m of the bedrock (Figure 7-3).

These weak, upward flow component conditions from the underlying brackish marine (Littorina) groundwaters, contribute to an important anthropogenic influence during near-surface sampling which mostly involves pumping from open percussion boreholes, some of which extend down to almost 200 m depth, i.e. to depths with a strong Littorina Sea component (Figure 7-5). Consequently, because of the hydraulic overpressure from depth these brackish marine (Littorina) groundwaters will tend to rise and mix with more surface-derived groundwaters under open borehole conditions, and ultimately these mixed groundwaters will be collected if the complete borehole length is being sampled. Mixing will be further enhanced when longer term pumping is employed.

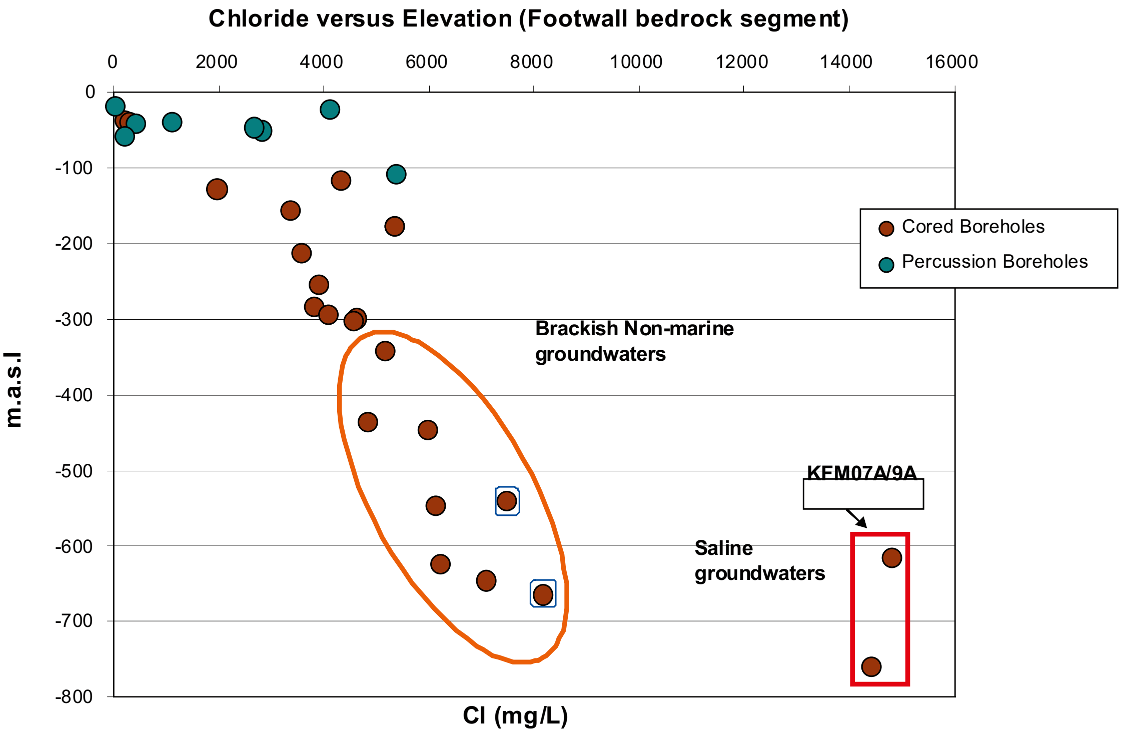


Figure 7-6. *Plot of quality assessed borehole chloride data (Categories 1–3) against elevation from the footwall bedrock segment (including fracture domains FFM01/02) showing; a) the distribution of the fresh groundwater (0–50 m), b) the presence of an intermediate to weak Littorina component (2,500–5,500 mg/L Cl) to ~300 m depth, c) the transition at 300 m to Brackish Non-marine (orange ringed), and d) the sharp transition to Saline (boxed) in the border zones outside the target volume. The two blue ringed samples represent updated F.2.3 data.*

Brackish Marine groundwaters (i.e. mostly Littorina-type groundwaters)

The series of gently dipping deformation zones in the hanging wall bedrock segment contain the bulk of the Littorina Sea waters which have entered, mixed and eventually come to rest when older brackish non-marine groundwaters of similar salinity were encountered (cf. Chapter 6). The average depth of penetration today is approximately to 600 m (Figures 7-3 and 7-5). This process may also have been influenced by a decrease in transmissivity with depth along the gently dipping deformation zones (cf. section 2.3).

Depending on the hydraulic character of the gently dipping deformation zones there is a fairly rapid depth transition of mixing from fresh recharge groundwater through the mixed brackish horizon (200–2,000 mg/L Cl) to weak Littorina-type groundwaters (~ 2,000–4,500 mg/L Cl; ~ 125–200 mg/L Mg; $\delta^{18}O \approx -10.3$ to –9.00‰ V-SMOW) to the main brackish marine (Littorina) groundwaters (~ 5,500 mg/L Cl; ~ 250–300 mg/L Mg; $\delta^{18}O \sim -8.5$‰ V-SMOW). Figure 7-5 shows this transition sequence of chloride with depth for the gently dipping deformation zones in the hanging wall segment underlining: a) the restricted fresh groundwater presence from 0–100 m, b) the narrow range of salinity for the strongest brackish marine (Littorina) member which extends from 100–550 m depth, and c) the scatter of salinity values in the ~ 3,000–5,000 mg/L Cl interval range reflecting fresh/brackish marine (Littorina) groundwater mixing processes in individual gently dipping deformation zones.

Despite being considered non-conservative because of its possible participation in water/rock reactions /Molinero et al. 2008/, magnesium is still a key Littorina Sea indicator. Figure 7-7 shows the transition sequence for magnesium where the highest values correspond to the strongest brackish marine (Littorina) member and intermediate values reflect differing mixing environments in the gently dipping deformation zones. Note that the highest values correspond to the shallow bedrock environment (HFM08, HFM19, HFM13 and KFM02A) and probably reflect the present-day upward groundwater flow component of brackish marine (Littorina) groundwaters along the gently dipping deformation zones (i.e. ZFMA2 for HFM19/13, ZFMA5 for HFM08 and ZFM866 for KFM02A). Some residual old Baltic Sea component cannot be excluded.

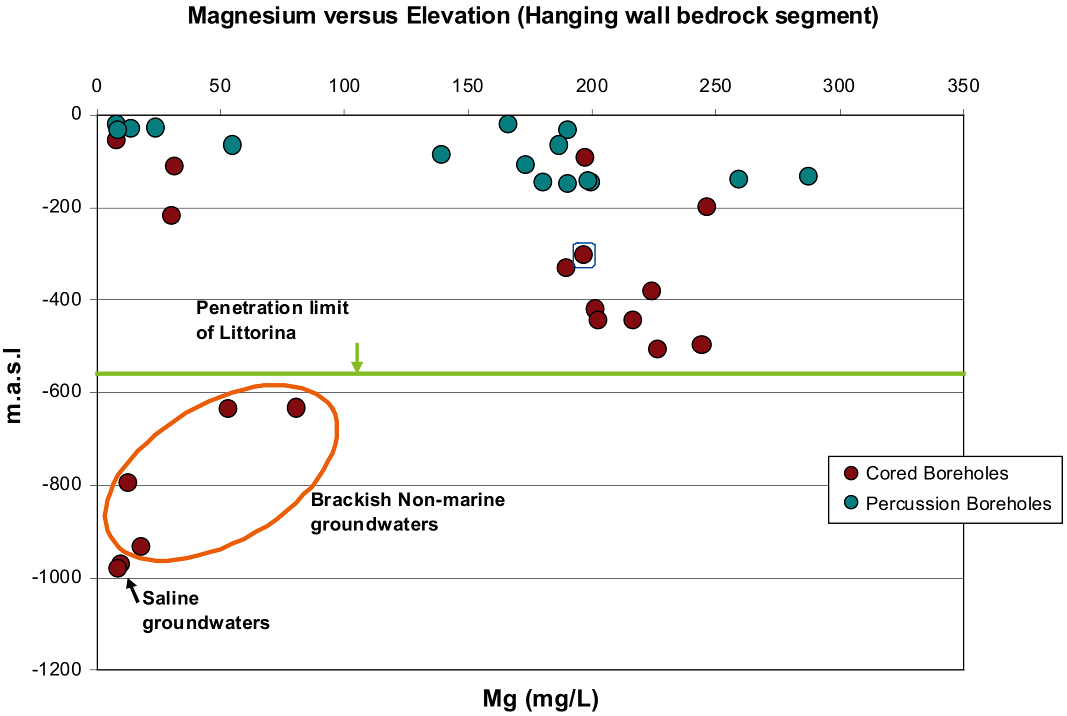


Figure 7-7. *Plot of quality assessed borehole magnesium data (Categories 1–3) versus elevation from the hanging wall bedrock segment showing: a) the depth extent of the high magnesium Littorina member (~ 550 m), b) the sharp transition between the Brackish marine (Littorina) and the Brackish Non-marine member (orange ringed) at around 600 m depth, and c) the gradual transition to the Saline member at (~1,000 m). The blue ringed sample represents updated F2.3 data.*

Groundwaters in the footwall bedrock segment (i.e. fracture domains FFM01 and FFM02) are characterised by a weak brackish marine (Littorina) signature down to 300 m and a general paucity of such groundwaters at greater depths. This paucity is illustrated in Figures 7-6 and 7-8 where chloride and magnesium are plotted against elevation. The chloride distribution is scattered but shows a mixing trend down to 300 m where there is a transition to the brackish non-marine member. This transition is better seen in Figure 7-8 where there is a decrease in magnesium at 300 m depth. KFM06C is an exception which can not be readily explained.

The upper 100–200 m of bedrock in the footwall bedrock segment (i.e. fracture domain FFM02) is considered to be hydraulically anisotropic due to a lattice of intersecting near-surface joints and gently dipping single fractures, i.e. the shallow bedrock aquifer (cf. sections 2.3.2/6.2.1). During the Littorina period the bedrock was under water with zero hydraulic gradient such that the Littorina Sea water penetrated downwards by density intrusion. The shallow bedrock aquifer subsequently became saturated by Littorina Sea water which persisted until recent land uplift established an increase in the hydraulic gradient. The bulk of the Littorina waters then were flushed out, a process which is still on-going, but relict Littorina Sea water is still present close to the bottom of the 'aquifer'. Evidence of penetration and mixing of the brackish marine (Littorina) groundwaters to greater depths below this horizon (i.e. down to 300 m) is best illustrated by data from borehole KFM01D, where subhorizontal to very gently dipping transmissive single fractures within the upper 300 m bedrock have been sampled (cf. Figure 7-3). Here the Littorina Sea component is weak to intermediate with chloride values mostly ranging from 2,500–4,500 mg/L, probably from mixing with fresh groundwaters during the on-going flushing out process. The gently dipping single fractures/fracture zones within the shallow bedrock aquifer may act as conduits bringing some brackish marine (Littorina) groundwaters down to around 300 m depth.

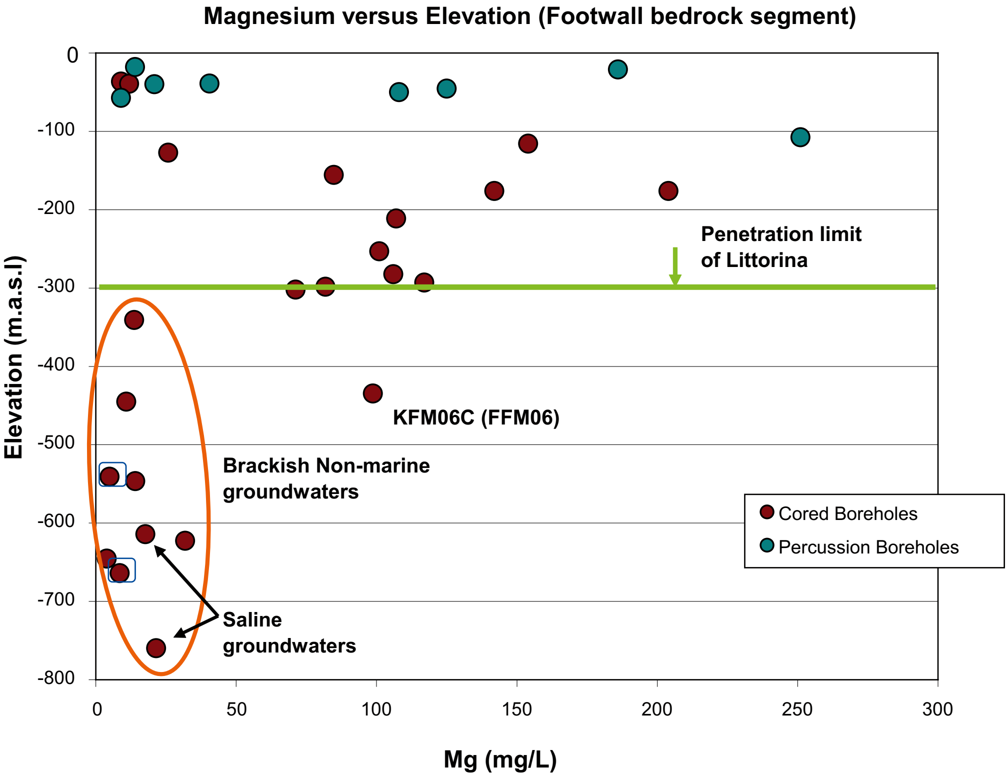


Figure 7-8. Plot of quality assessed borehole magnesium data (Categories 1–3) versus elevation from single fracture groundwaters in the footwall bedrock segment (i.e. fracture domains FFM01/02) and the border zone boreholes KFM09A and KFM07A outside the target volume. These show the maximum depth extent of the high magnesium Brackish marine (Littorina) member to 300 m, which coincides with the transition to the low magnesium Brackish Non-marine member. KFM06C is anomalous and is located in fracture domain FFM06. The two ringed samples represent updated F2.3 data.

Brackish Non-marine groundwaters (i.e. Old Meteoric ± Old Glacial ± Last Deglaciation meltwater + Saline groundwaters)

In the hanging wall bedrock the transition from brackish marine (Littorina) type groundwaters to the brackish non-marine groundwaters is quite sharp and occurs at around 550–600 m depth (Figures 7-5 and 7-7). From 600–930 m depth chloride increases steadily from 5,500–8,500 mg/L before levelling out at just under 10,000 mg/L at 1,000 m depth, i.e. the transition to the saline member. Over the same interval magnesium indicates a decrease from 80.2–17.6 mg/L before levelling out at < 10 mg/L at 1,000 m.

In the footwall bedrock the situation differs in that just below 300 m the brackish non-marine member becomes dominant and changes little in salinity (close to 6,000 mg/L Cl) to just over 600 m depth where it increases to around 7,000 mg/L Cl. There are inadequate data at the moment to indicate the nature of the salinity increase (i.e. gradual or sharp) at depths greater than 600 m.

Saline groundwaters

The most saline groundwaters are Ca-Na-Cl in type (Ca:Na = 2.1–2.7), found in KFM03A at just under 10,000 mg/L Cl, and in KFM07A and KFM09A (14,400 and 14 800 mg/L Cl respectively) which are located outside the target volume to the north-west (Figures 7-2 and 7-4). For comparison, the deepest groundwaters at Laxemar and Olkiluoto show Ca:Na ratios of 2.3 and 4.2 respectively. At both Laxemar and Olkiluoto there is a clear evolution via Na-Ca-Cl to Ca-Na-Cl types. At Forsmark Na-Ca-Cl types are represented by the brackish marine member (i.e. Littorina-type groundwaters) and the transition to Ca-Na-Cl types coincides with the change to the brackish non-marine member.

The higher salinities at intermediate depths referred to as 'Upconing compositions' in Figure 7-4 (boreholes KFM07A and KFM09B) may be explained by anthropogenic activities, but may also reflect natural effects due to glacial rebound after the maximum glacial loading (cf. section 5.10.2).

7.2.4 Supporting hydrochemical evidence for the groundwater distributions

The above discussion of groundwater types and their subdivisions with respect to elevation and chemistry is largely based on salinity because of its direct correlation with depth and specific water types, and magnesium because of its sensitivity to the Littorina Sea water component. Other chemical parameters, however, also generally support the subdivisions as visualised in Figure 7-3 and Figure 7-4 and indicated in sections 5.8, 5.9 and 6.3).

Figures 7-9 to 7-15 illustrate the use of various chemical parameters to generally support the four groundwater subdivisions based on the depth relations of magnesium and chloride described in the previous section, i.e. Fresh meteoric-type groundwaters, Brackish Marine groundwaters (i.e. mostly Littorina in type), Brackish Non-marine groundwaters and Saline groundwaters. Figures 7-9 and 7-10 plot calcium against sodium with data grouped according: a) to three chloride compositional ranges using all data (Categories 1–5) apart from Tube samples, and b) introducing the fresh water range of < 200 mg/L Cl and confining the data to quality Categories 1–3. This exercise was carried out to ensure that no other possible groundwater groups or details had been overlooked.

Figure 7-9, using all data, differentiates a clear brackish to saline non-marine group with Ca>Na, and also the brackish marine (Littorina) group with Na>Ca. At lower salinities the situation is less clear due to mixing (from 0–300 m depth) between different water types, including both non-marine fresh recharge waters and marine waters, possibly of old Baltic Sea origin. Figure 7-10 provides a much simpler and clearer picture, mainly because good quality data have been used. More clearly differentiated are the Littorina-type groundwaters and also the shallow fresh meteoric waters. Furthermore, there is now an indication of an overlap between the brackish non-marine and the brackish marine Littorina-type groundwaters, and the mixed variant

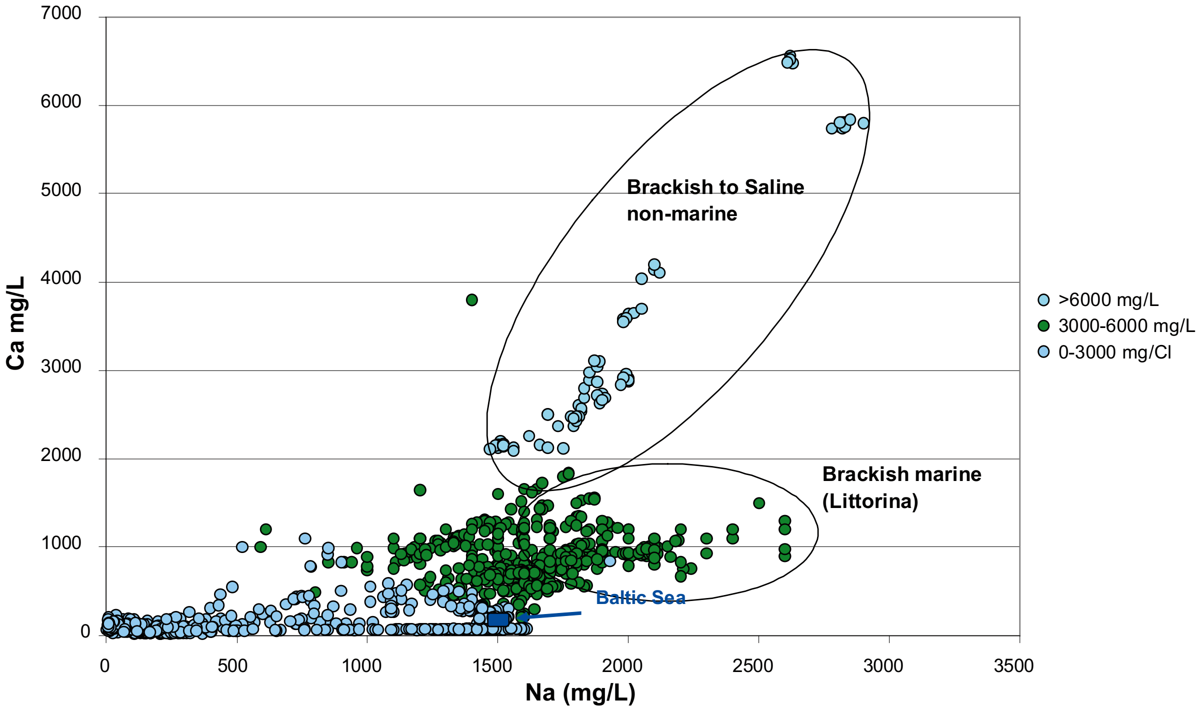


Figure 7-9. Plot of calcium against sodium using all data apart from Tube samples (exception KFM09B).

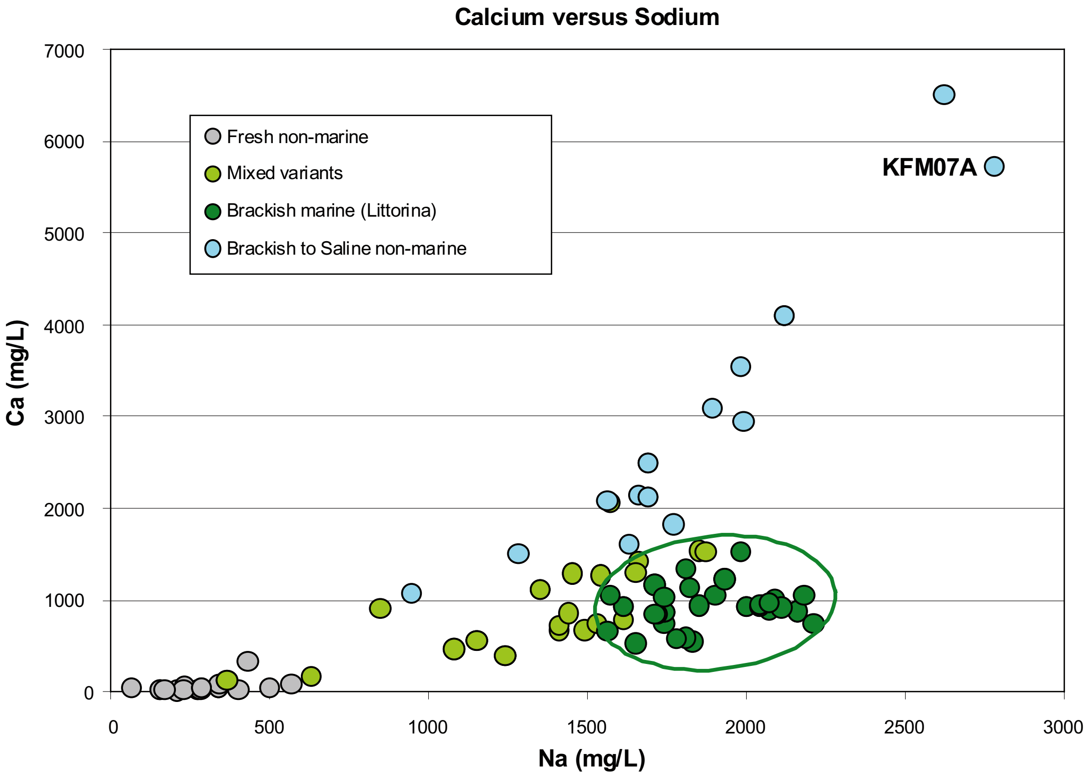


Figure 7-10. Plot of calcium against sodium using only Category 1–3 data. Predominantly marine brackish (Littorina) groundwater are ringed.

samples suggest some mixing is occurring between them and also between the Littorina-type groundwaters and the shallower fresh waters. This latter mixing is particularly associated with the transmissive, gently dipping deformation zones characterising the hanging wall bedrock segment and to a lesser extent the open fractures characteristic of the uppermost footwall bedrock segment (i.e. fracture domain FFM02). At shallow depths mixing is a product of natural hydraulic gradients in the area, but anthropogenic mixing is also widespread due to different borehole activities. Mixing between the brackish marine (Littorina) and the brackish non-marine groundwaters was also indicated by the depth-related plots (cf. section 6.2.3) and occurs mainly at depths around 500–600 m depth.

Figures 7-11 and 7-12, plotting magnesium against bromide, show an even clearer separation between the brackish to saline non-marine and the brackish marine (Littorina) groundwaters. Figure 7-13 with the mixed variant groundwaters shows the two mixing trends involving the brackish Littorina type groundwater, one towards shallower depths (low Br) and the other to greater depths (high Br and low Mg).

Figure 7-14 using magnesium and $\delta^{18}O$ produces at first glance a high degree of scatter which is considerably simplified by Figure 7-15 to show that the Littorina type groundwater is separated from the non-marine types by high magnesium and enriched $\delta^{18}O$; the most depleted $\delta^{18}O$ signatures are associated with the brackish to saline non-marine groundwaters; meanwhile the fresh waters have typical recharge values. Figure 7-14, however, by using all data, manages to provide more interesting details. The figure illustrates three possible mixing lines representing: a) present Baltic sea and present meteoric waters with constrained $\delta^{18}O$ values ranging from approximately –12.3 to –11.2‰ V-SMOW and low to moderate magnesium contents (0–200 mg/L), b) Littorina + last deglaciation and brackish to saline non-marine trends where $\delta^{18}O$ values indicate cold climate recharge conditions (–14.1 to –12.5‰ V-SMOW) reflecting the possibility of both old glacial and last deglaciation input, and the range of magnesium (around 50–200 mg/L) now dominated by the Littorina input, and c) the potential trace of mixing between the Littorina and last deglaciation events where higher magnesium (to just below 350 mg/L Cl) and more depleted $\delta^{18}O$ values would be expected.

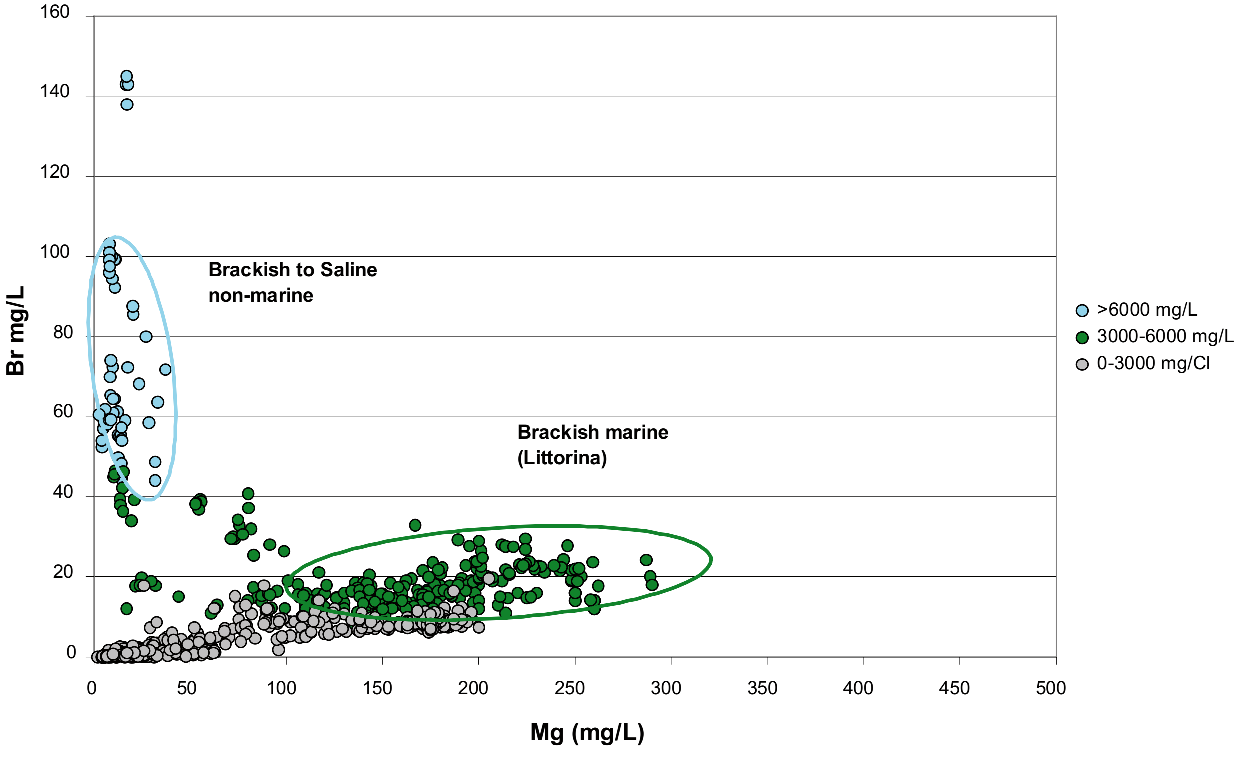


Figure 7-11. *Plot of bromide against magnesium using all data apart from tube samples (exception KFM09B).*

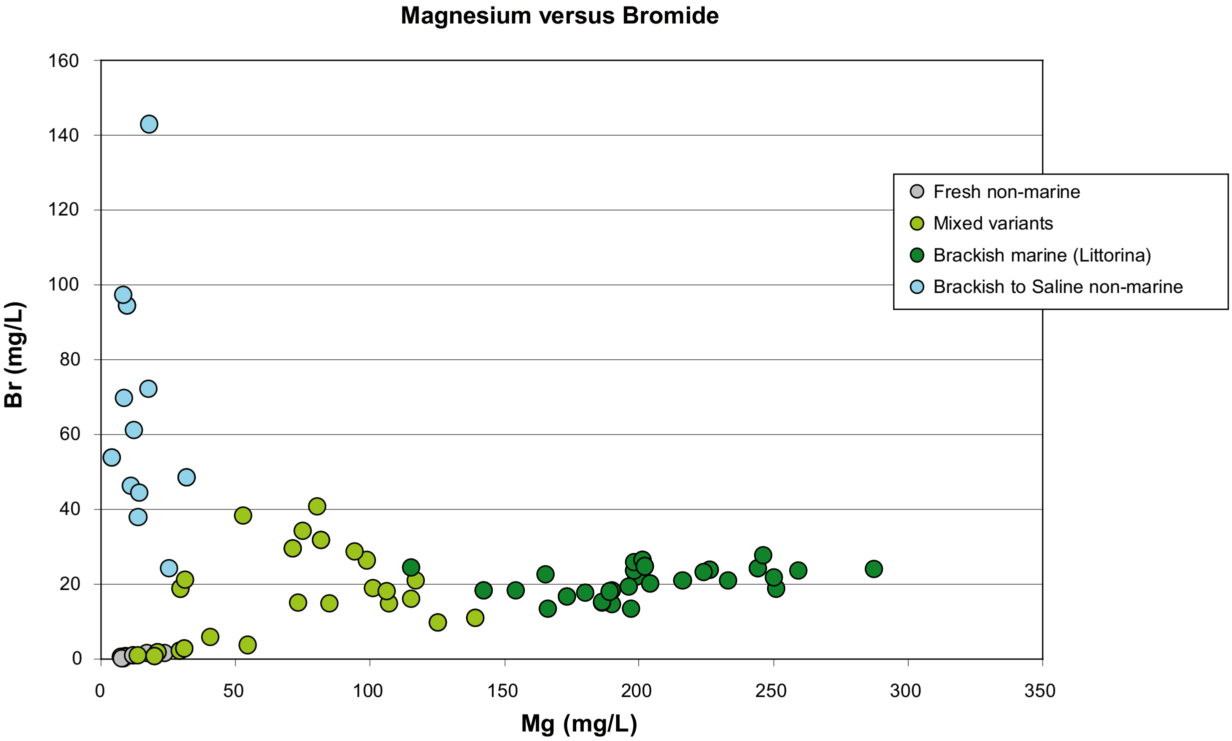


Figure 7-12. Plot of bromide against magnesium using only Category 1–3 data.

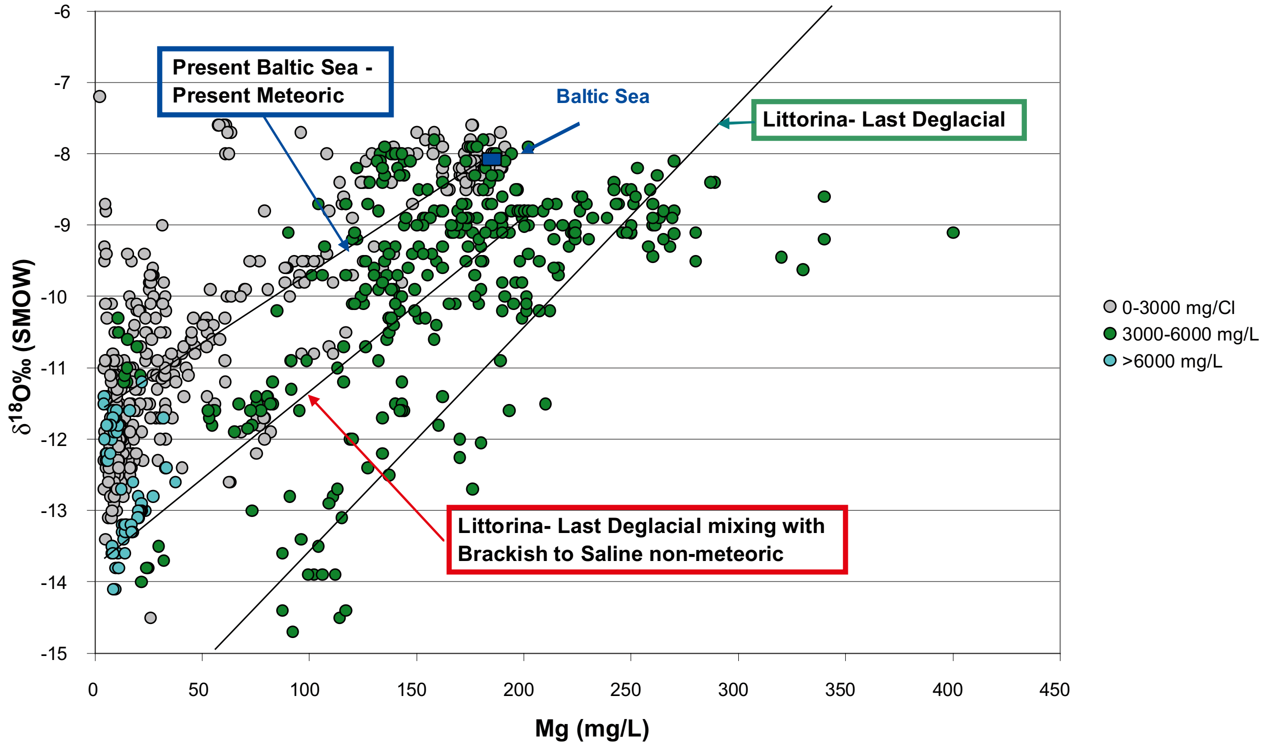


***Figure 7-13.** Plot of $\delta^{18}O$ against magnesium using all data apart from tube samples (exception KFM09B).*

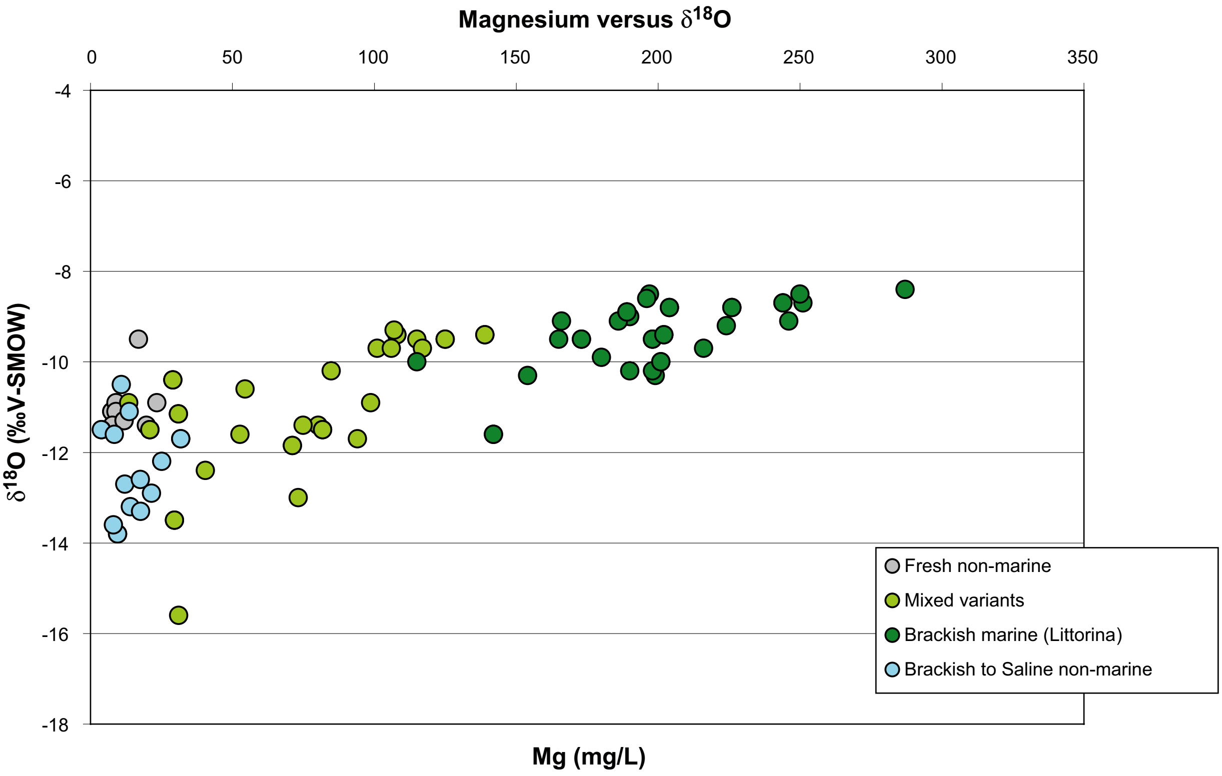


***Figure 7-14.** Plot of $\delta^{18}O$ against magnesium using only Category 1–3 data.*

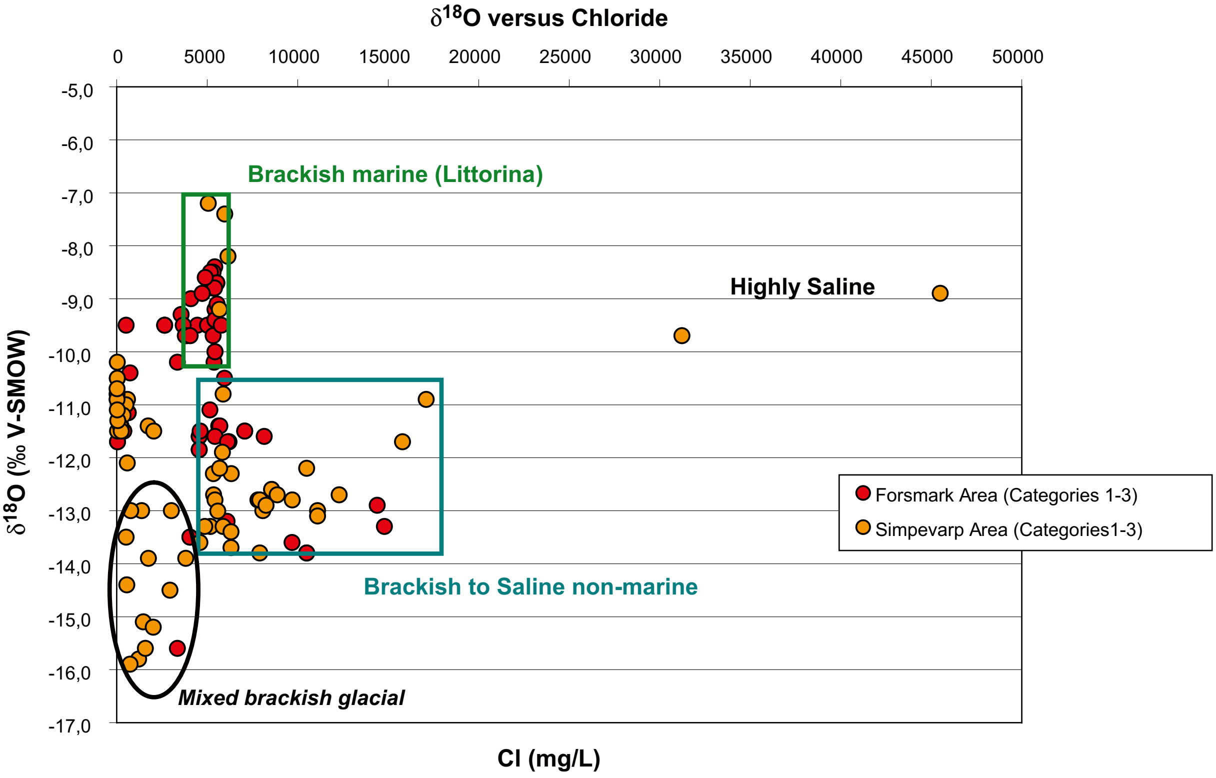


***Figure 7-15.** Plot of $\delta^{18}O$ against chloride for groundwater samples from the Forsmark and Laxemar-Simpevarp area using only Category 1–3 data.*

Finally, Figure 7-15 uses all Category 1–3 borehole data to compare the Forsmark and the Laxemar-Simpevarp area. Immediately obvious are the similarities in the major groundwater groups from both areas, the main exception being the presence of highly saline groundwaters in the Laxemar area. Of some interest is one Forsmark sample (KFM12A) which plots together with several groundwaters from the Laxemar-Simpevarp area representing brackish waters (0–3,500 mg/L Cl) with a large glacial meltwater component (–16 to –13‰ V-SMOW) and generally low magnesium (< 100 mg/L). What many of these samples have in common is that they originate from (or close to) large-scale regional deformation zones.

7.2.5 Distribution of groundwater types in the WSW-ENE cross-section

The different groundwater types which characterise the WNW-ESE cutting plane (Figure 7-4) correspond to those used in the WNW-ESE cutting plane discussed in section 7.2.4 for Figure 7-3. In addition, the variation of these groundwater types with depth are integrated and therefore based on the same plots (i.e. Figures 7-6 to 7-15 including F.2.3-updated data from KFM08D) used to interpret the WNW-ESE cutting plane.

As mentioned earlier, visualisation of the WSW-ENE cross-section (Figure 7-4) is more problematic than the WNW-ESE cross-section because of the absence of a structural framework to show the variation in chlorinity and the location of the different groundwater types. In the absence of a framework, chloride contents and groundwater types are restricted to the sampling location points. Despite this drawback, however, the hydrochemical data available and their distribution in the target volume confirm the character and trends discussed in section 7.2.4 in relation to the footwall bedrock segment.

Fresh groundwaters

In common with Figure 7-3, fresh groundwaters waters in the uppermost part of the footwall segment (i.e. fracture domain FFM02) are restricted to the shallow bedrock aquifer which extends from 50–200 m depth. Percussion boreholes HFM20, 23 and 28, penetrating to depths of 150–300 m, recorded fresh groundwater compositions. However, these samples were taken from the complete borehole sections and unfortunately there are no Flow Log measurements to indicate the position of the main inflow points to the sampled borehole lengths. These sampled percussion boreholes are therefore represented in Figure 7-4 as infilled cylinder shapes.

Mixed brackish groundwaters

There is some evidence of anthropogenic effects, i.e. mixing of fresh water and brackish marine (Littorina/Baltic Sea) groundwaters, during drilling and subsequent sampling. These affects appear to have influenced mostly the groundwaters sampled within the gently dipping deformation zone 1203. Here, there is some evidence of mixing along borehole HFM21 between fresh and brackish marine (Littorina/Baltic Sea) groundwaters, and possibly also in the upper borehole section of borehole KFM08A (where it intersects zone 1203) between a glacial water and a non-marine saline component, although this latter type could equally well represent a naturally mixed sample.

Brackish marine groundwaters

Residual brackish marine groundwaters (both of Littorina and/or Baltic Sea in origin) are restricted mostly to the near surface, gently dipping deformation zone 1203. Percussion boreholes HFM21, 22 and 38 show a range of chloride from 3,000–4,110 mg/L, magnesium from 108–186 mg/L and $\delta^{18}O$ from –9.5 to –9.1‰ V-SMOW, all suggesting a Littorina and/or Baltic Sea component.

Some additional residual marine components may be associated with the shallow bedrock aquifer and also to connected open single fractures at somewhat greater depths (i.e. to 100–250 m). There are, however, inadequate data available to support this latter statement.

The deepest penetration of the brackish marine (Littorina/Baltic) groundwaters in the upper part of the footwall bedrock is estimated to be around 200–250 m, somewhat less than indicated in the WNW-ESE cross-section shown in Figure 7-3 due to the close proximity of the major ZFMA2/ZFMF1 gently dipping deformation zones.

Brackish non-marine groundwaters

The brackish non-marine groundwaters with a weak cold climate signature extend from around 250 m to 800 m depth and show a range of chloride from 6,110–8,350 mg/L, magnesium from 2.6–28.5 mg/L and $\delta^{18}O$ from –13.3 to –11.6‰ V-SMOW. The slightly higher magnesium contents (> 15 mg/L) in some samples represent the transition type samples described in section 7.2.4.

Saline groundwaters

Within the target volume there are no available hydrochemical data for saline groundwaters. Boreholes KFM07A and KFM09A, however, are angled to the north-west and penetrate rock domains RFM044 and RFM012 just outside the target volume (cf. Figure 2-7). The groundwater compositions taken from these boreholes at vertical depths of 816.33 m and 616.55 m respectively are similar, ranging from 14,400–14,800 mg/L Cl, 21.5–17.7 mg/L Mg and –13.30 to –12.9‰ V-SMOW $\delta^{18}O$. The presence of these saline groundwaters at the sampling depths indicated is not considered to be representative, but rather it is thought to be due to upconing effects during borehole activities which included the sampling campaign. This possibility of anthropogenic upcoming, together with the evolved chemical signatures of these saline groundwaters (cf. section 5.9), indicate a depth of origin certainly to 1,000 m, if not deeper. This explains the allocation of 'Saline groundwater' to boreholes KFM07A and KFM09A in Figure 7-4.

Highly Saline groundwaters

There are no data from greater depths where highly saline groundwaters probably reside (cf. section 5.8).

Groundwater types close to the Singö DZ

Two percussion boreholes (HFM34 and 35) and one cored borehole (KFM11A) have been drilled outside the target volume, ENE of the cross-section, with the main purpose of characterising the major Singö Deformation Zone (DZ) (Figure 7-4). Percussion borehole HFM33 was used as a drilling water source to KFM11A. Several distinctive groundwater types can be recognised: a) Brackish marine (Littorina) type from HFM33 drilled to a vertical depth around 136 m (5,350 mg/L Cl, 251 mg/L Mg, $\delta^{18}O$ = –8.7‰ V-SMOW), b) Brackish marine (Baltic Sea water) type from HFM34 and HFM35 drilled to vertical depths of 82.92 m and 78.24 m respectively (2,600 mg/L Cl, 147–170 mg/L Mg, $\delta^{18}O$ = –8.3‰ SMOW), c) Brackish non-marine type sampled from KFM11A at a vertical depth of 389.68 m just outside the Singö DZ (4,550 mg/L Cl, 25.1 Mg, $\delta^{18}O$ = –12.2‰ V-SMOW), and d) once again a brackish marine (Littorina) type sampled at vertical depth of 593.76 m in KFM11A, inside the Singö DZ (4,410 mg/L Cl, 115 mg/L Mg, $\delta^{18}O$ = –10.0‰ V-SMOW).

Despite the lack of data, it is possible to some extent to correlate the hydrochemistry within the target volume with the surrounding rock domains to the north-east beyond sub-vertical deformation zone WNW 0809A (Figure 7-4). There is a similar upper 200–250 m depth where brackish marine groundwater types exist, and the single brackish non-marine sample from borehole KFM11A correlates favourably with groundwaters in the tectonic lens at the same depth. As might be expected, in the major Singö DZ itself groundwaters of marine origin occur at greater depths. At still greater depths, older brackish non-marine and more glacial types might be expected, but no data exist. No attempt has been made to extrapolate groundwaters further to the north-east beyond the Singö DZ.

7.2.6 Rock matrix porewaters

Background details to the porewater studies at Forsmark are presented and discussed in /Waber et al. 2008/. As an important contribution to the construction of the Forsmark site visualisation presented in Figures 7-3 and 7-4, this present section will concentrate on the distribution of porewater chloride with depth and how this is interfaced with the spatial distribution of the fracture groundwater hydrochemistry described above.

Rock matrix porewaters have been analysed from five boreholes of which three are located in the footwall bedrock segment (i.e. fracture domains FFM01 and FFM02; KFM06A, KFM01D and KFM08C), one in the hanging wall bedrock segment (i.e. KFM02B), and one located just outside the target volume to the north-west (KFM09B). With the exception of KFM09B, samples for study were collected at regular intervals along the complete core lengths; no samples exist from the upper 100 m percussion drilled part of the boreholes. Studies of borehole KFM09B were confined to a short length of core (around 13 m drillcore length at a vertical depth of 469.76–480.49 m) from an altered vuggy granite horizon to assess its impact on the porewater composition. These data have not been used in the present visualisation as they are from outside the target volumn.

For the Forsmark WNW-ESE visualisation (Figure 7-3) only porewater data from KFM02B (parallel with the cross-section) and KFM01D (perpendicular to the cross-section) can be evaluated approximately on the selected cross-section, and for the WSW-ENE visualisation KFM11A, KFM07A and KFM09A which are close to parallel to the cross-section (Figure 7-4). Taking all the borehole data collectively, however, there is enough information to be able to estimate the expected porewater chemistry based on depth considerations, hydrogeology and hydrochemical knowledge of the site.

Porewater scenario

Conceptually, the Fennoscandian bedrock can be considered a simple hydrogeological dynamic system with high fracture frequency and transmissivities in the upper approximately 300–400 m (i.e. more dynamic flow conditions), lower fracture frequency and transmissivities at intermediate depths (i.e. low flow conditions), and decreasing flow to stagnant conditions at depths greater than 1,000 m. The fracture groundwater salinity also increases systematically within these depth intervals and, for this present scenario discussion, it is also assumed that the salinity of the rock matrix porewaters mirrors that of the fracture groundwaters, i.e. a diffusion steady state has been established at each depth interval throughout the bedrock.

If this system is now perturbed by a single external event, for example, the deep incursion of dilute glacial meltwater over a certain period of time, steady state conditions will change to transient conditions due to the change in fracture groundwater chemistry, i.e. concentration gradients will become established between the rock matrix porewater and fracture groundwater. The extent of such established transient conditions depends on the distance between water-conducting fractures, the accessibility of the pore-water (i.e. interconnected porosity), and the time to change the groundwater composition in the fracture. During the time interval of such a glacial meltwater incursion, a return to steady-state conditions would be expected to occur:

More rapidly between fracture groundwaters and rock matrix porewater in the upper bedrock because of the high frequency and small distance between the water-conducting fractures, and the circulation of large volumes of meltwater.

Less rapidly at intermediate depths because of lower fracture frequency, more widely spaced fracture systems and lower flow rates, i.e. restricted circulation of meltwater. However, close to steady state may be achieved at some individual locations of increased fracture frequency and transmissivity.

At greater depths characterised by even fewer, low transmissive fractures, the initial impact of the glacial meltwater will be small (if present at all) due to volume restrictions and the high salinity of the fracture groundwaters. Small changes in steady-state conditions may occur, but will be of minor importance with little observable salinity difference between the porewaters and the fracture groundwaters.

Observations from Forsmark

Using this scenario as a background framework, and then coupling it to porewater observations in the rock matrix along cross-sections in Figure 7-3 and 7-4, plays an important part in the constructing the two visualisations. The situation prior to the last deglaciation at Forsmark is not known with certainty, but the widespread presence of the brackish non-marine groundwater (i.e. Old Meteoric ± Old Glacial + Saline member) in the rock matrix and as groundwater in the fractures (shown by ^{36}Cl to be at least 1.5 Ma old; section 5.9) points to a long uninterrupted period of transient conditions, at least at depths greater than approximately 600 m, and possibly at shallower depths. Then came the last deglaciation event followed quite rapidly by the Littorina Sea transgression, and now by present day fresh meteoric recharge water. Porewater studies have shown that during these rapidly changing (in geological terms) hydrochemical conditions, the time interval between the different events has been too short to allow steady-state conditions to become established for any one event. Two exceptions to a lack of observed steady state conditions are, however, still possible: a) in the very upper 0–100 m which is highly fractured and water conductive, and b) in areas of bedrock close to individual but highly transmissive deformation zones at low to intermediate depths. Unfortunately no core material is available from the 0–100 m depth interval at Forsmark to support possibility (a) as percussion drilling techniques have been used. There is, however, some evidence to support possibility (b) in close proximity to the large-scale ZFMA2 deformation zone (i.e. see diffusion profile data from KFM02B /Waber et al. 2008/.

Reflecting the above-described scenario for the Fennoscandian bedrock, the upper bedrock at Forsmark is characterised by an increase in fracture frequency and transmissivity (i.e. dynamic hydrological conditions), and there is commonly still some disparity between porewater chemistry compared to the fracture groundwater chemistry, indicating that steady-state conditions between porewater and present-day fracture groundwater are close to being achieved, but require more time. With increasing depth there is normally a decrease in fracture frequency and transmissivity (i.e. less dynamic hydrological conditions) and the disparity between the rock porewater and the present-day fracture groundwater is often greater than at shallower, more conductive bedrock levels. Localised exceptions occur in the immediate vicinity of individual more transmissive deformation zones. Eventually, depths are encountered where water-conducting fractures are few, steady-state palaeo-conditions remain established, and the porewater chemistry is broadly similar to that of the fracture groundwaters. These depths have been influenced to some limited extent by one or more glacial events of unknown age (i.e. along some of the more major transmissive fractures), but recent post-glacial events (i.e. Littorina Sea incursion) have had very little impact and steady-state conditions are more advanced.

It is clear, therefore, that the hydraulic properties of the rock mass are critical in explaining the present and past rock porewater distribution and its chemistry, in the same way as for the fracture groundwater chemistry described above.

Based on hydrogeological studies, generally four depth environments can be considered extending from 0–150 m, 150–600 m, 600–1,000 m and > 1,000 m, and correspond to the subdivisions discussed in sections 7.2.3 and 7.2.4 derived from the salinity and other chemical indicators. The most sensitive interval to 150–600 m depends on the localisation, for example, there is a clear depth interval associated with the hanging wall bedrock area where groundwater flow conditions in the gently dipping deformation zones are dynamic with a series of transmissive, gently dipping deformation zones penetrating to depth. In contrast, the upper approximately 100–600 m of the footwall bedrock comprises an upper, highly conductive volume (i.e. fracture domain FFM02), and a lower, less conductive volume (i.e. fracture domain FFM01). Excluding the upper highly conductive shallow bedrock aquifer, which characterises the approximate 0–20 m interval, the remaining footwall bedrock segment is less conductive and tends to be more dominated by gently dipping to subhorizontal single fractures down to around 600 m depth.

WNW-ESE cross-section

In the footwall bedrock area (i.e. the target volume) of this cross-section (Figure 7-3), porewater data are available from KFM01D and KFM06A. Here, the porewater chloride concentrations below 1,500 mg/L are only locally observed at shallow levels down to around 200 m (e.g. borehole KFM06A); this contrasts to the hanging wall bedrock (borehole KFM02B) where the porewater salinities seem to be consistently low down to at least approximately 400 m (700–1,500 mg/L Cl) and probably locally deeper to approximately 600 m due to the close vicinity of the gently dipping deformation zones.

At approximately 600–700 m depth in both the hanging wall and footwall segments there is a sharp shift to higher porewater salinities (3,500–7,000 mg/L Cl). At greater depths, maximum porewater concentrations of around 12,000 mg/L Cl occur below about 800–900 m in each of the bedrock segments. Although there are very few deep corresponding groundwater data, it is probable that the increase in porewater salinity is accompanied by an increase in fracture groundwater salinity.

At greater depths below 1,000 m there are no porewater or groundwater chemical data. However, it is reasonable to assume that steady-state (or very close) conditions will be widespread and that projected groundwater salinities (i.e. > 20,000 mg/L Cl) will also characterise the rock matrix porewaters.

WSW-ENE cross-section

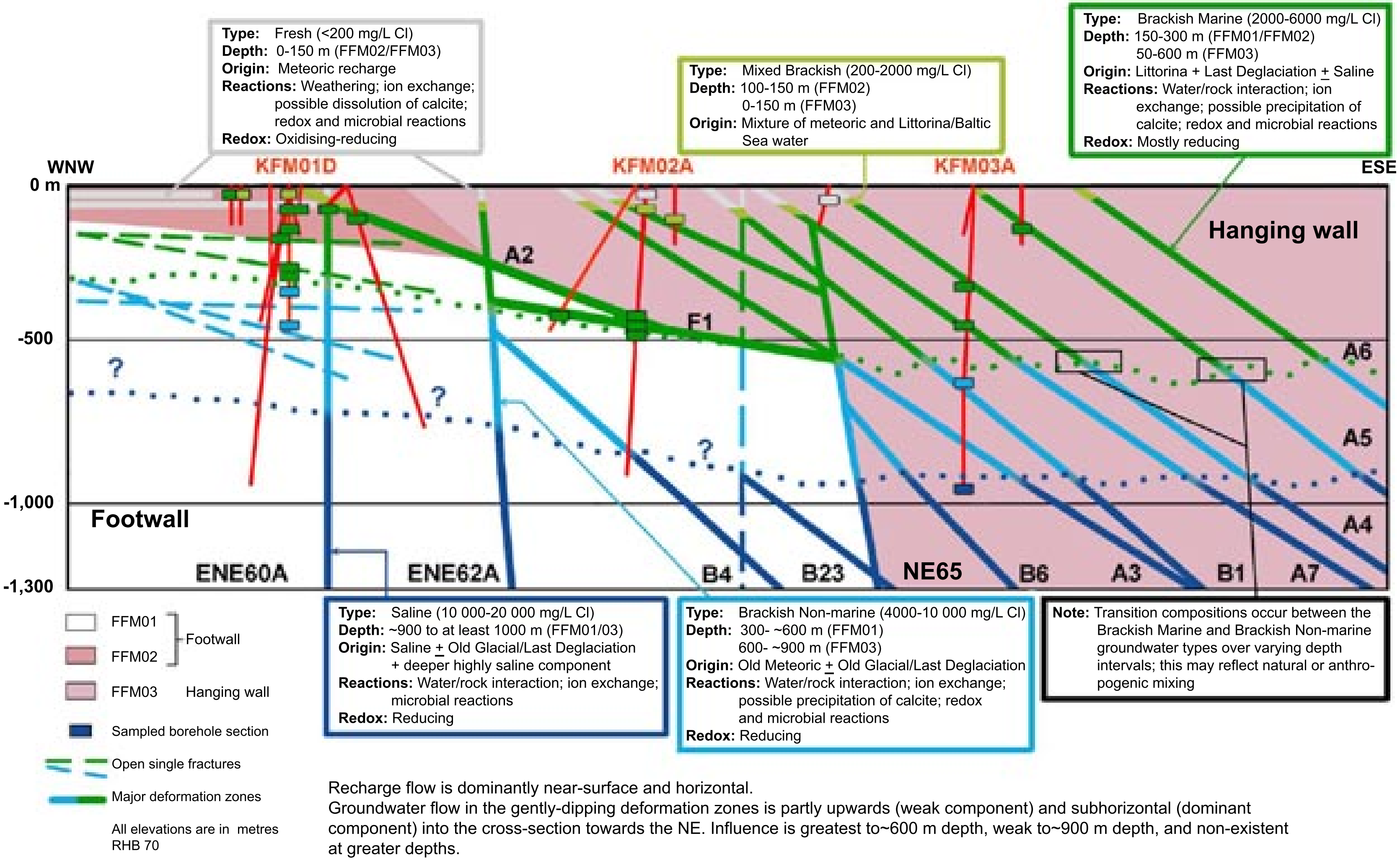
In the WSW-ENE cross-section (Figure 7-4), rock matrix porewater data have been produced from along the full length of borehole KFM08C and also a short approximate 13 m profile through an episyenite (‘vuggy granite’) zone in KFM09B. The data from borehole KFM08C provided the basis to the porewater distribution where the same porewater chloride subdivisions for the WNW-ESE cross-section in Figure 7-3 are used. There is a subdivision of lower porewater chloride values (2,000–3,500 mg/L) in the upper approximate 350 m of bedrock, then an increase (to 3,500–7,000 mg/L) from around 350–700 m, and finally 7,000–20,000 mg/L from around 700– >1,000 m. It is assumed at greater depths that the porewaters are > 20,000 mg/L Cl and at or close to steady-state conditions with the fracture groundwater salinity (i.e. highly saline groundwaters). Close to steady-state conditions are also suggested between the rock porewaters and the brackish non-marine groundwaters, at depths around 500–700 m, and for the saline groundwaters at depths of 800– >1,000 m.

Although borehole KFM09B data are restricted in their use; most porewater values between 470–480 m depth fall within the range of 4,500–6,500 mg/L Cl which conform with KFM08C at that depth, and therefore suggest close to steady-state conditions with the fracture groundwaters. The two remaining samples in the profile give values of around 8,600 mg/L Cl and 10,500 mg/L Cl respectively, and probably indicate rock areas of lower permeability containing an older, more saline component where transient conditions with the fracture groundwaters are still active.

In general, these porewater distributions generally agree with those observations for the footwall bedrock porewaters discussed above for the WNW-ESE cross-section.

7.2.7 Complementary visualisations

Modified visualisations have been constructed to clarify the location of the hanging wall and footwall bedrock segments, and their subdivision into fracture domains FFM01, FFM02 and FFM03 (Figures 7-16 and 7-17). Included in the visualisations are brief summaries of the chlorinity, depth intervals, origin, the main reactions and the redox conditions for each groundwater type. Whilst mixing (both advection-dispersion and molecular diffusion) is the major process giving rise to present-day groundwater compositions, the role of important reactions has also been addressed ranging from weathering and potential calcite dissolution in the near-surface bedrock environment, to possible calcite precipitation at intermediate levels and long-term water/rock interaction being dominant in the deep bedrock characterised by decreasing flow to stagnant groundwater conditions. Microbially-mediated reactions (e.g. iron-reducing and sulphate-reducing bacteria) occur, particularly in the shallow to intermediate depths where active groundwater flow is occurring. Redox conditions range from oxidising/reducing near the surface to reducing with increasing depth.



Type: Fresh (<200 mg/L Cl)
Depth: 0-150 m (FFM02/FFM03)
Origin: Meteoric recharge
Reactions: Weathering; ion exchange; possible dissolution of calcite; redox and microbial reactions
Redox: Oxidising-reducing

Type: Mixed Brackish (200-2000 mg/L Cl)
Depth: 100-150 m (FFM02)
0-150 m (FFM03)
Origin: Mixture of meteoric and Littorina/Baltic Sea water

Type: Brackish Marine (2000-6000 mg/L Cl)
Depth: 150-300 m (FFM01/FFM02)
50-600 m (FFM03)
Origin: Littorina + Last Deglaciation ± Saline
Reactions: Water/rock interaction; ion exchange; possible precipitation of calcite; redox and microbial reactions
Redox: Mostly reducing

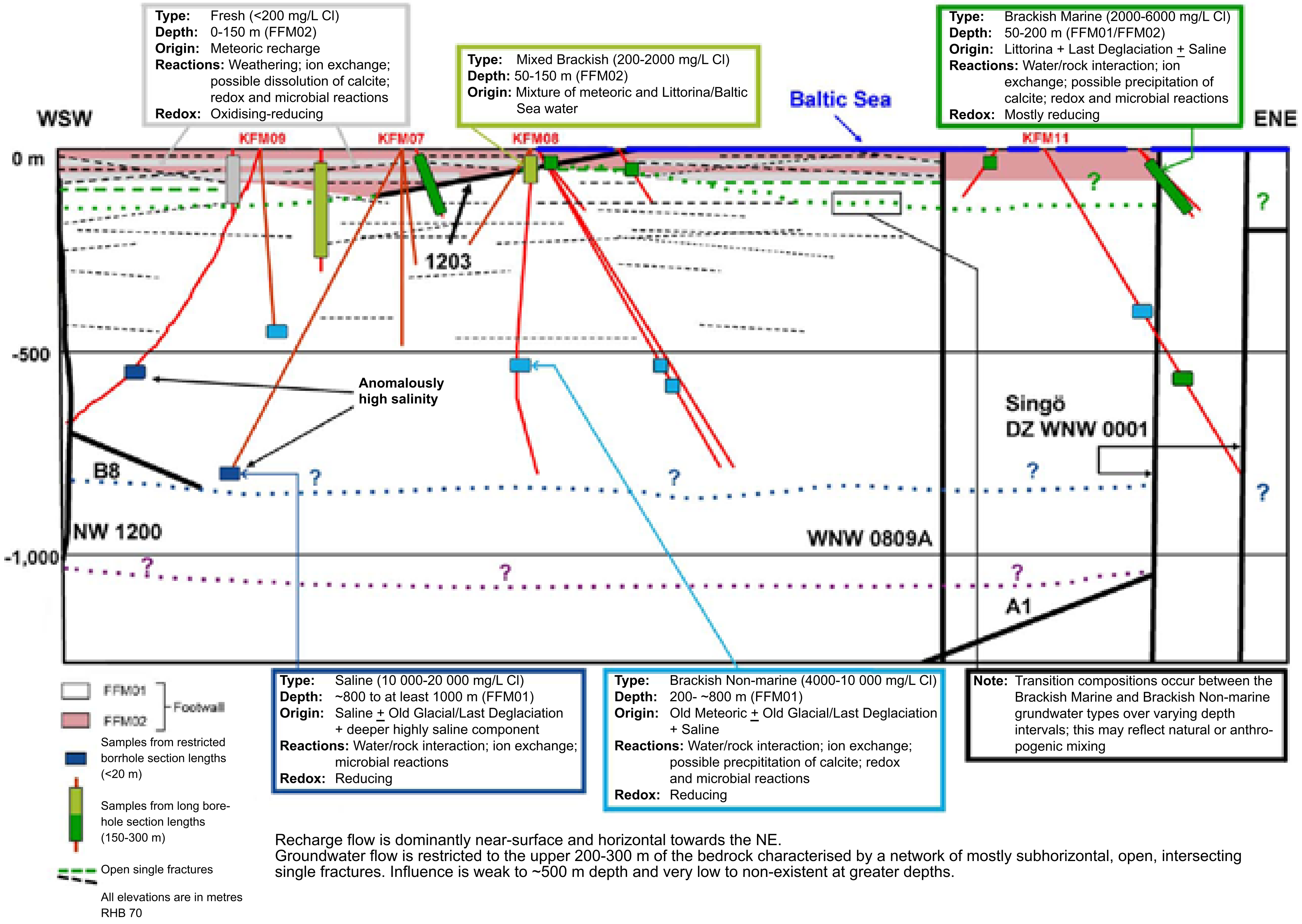
Type: Saline (10 000-20 000 mg/L Cl)
Depth: ~900 to at least 1000 m (FFM01/03)
Origin: Saline ± Old Glacial/Last Deglaciation + deeper highly saline component
Reactions: Water/rock interaction; ion exchange; microbial reactions
Redox: Reducing

Type: Brackish Non-marine (4000-10 000 mg/L Cl)
Depth: 300- ~600 m (FFM01)
600- ~900 m (FFM03)
Origin: Old Meteoric ± Old Glacial/Last Deglaciation
Reactions: Water/rock interaction; ion exchange; possible precipitation of calcite; redox and microbial reactions
Redox: Reducing

Note: Transition compositions occur between the Brackish Marine and Brackish Non-marine groundwater types over varying depth intervals; this may reflect natural or anthropogenic mixing

Recharge flow is dominantly near-surface and horizontal.
Groundwater flow in the gently-dipping deformation zones is partly upwards (weak component) and subhorizontal (dominant component) into the cross-section towards the NE. Influence is greatest to~600 m depth, weak to~900 m depth, and non-existent at greater depths.

Figure 7-16. *WNW-ESE 2D cross-section through the central part of the candidate area showing the groundwater types and their properties (salinity, origin, major reactions and redox conditions). The footwall (FFM01 and FFM02) and hanging wall (FFM03) bedrock segments are indicated, separated by the major gently dipping deformation zones ZFMA2 and ZFMF1 (abbreviated to A2 and F1), and the steeply dipping deformation zone ZFMNE0065. The dotted lines in different colours crossing the section represent the approximate depths of (or extrapolation of) penetration of the different groundwater types along hydraulically-active deformation zones. (Cross-section length = 6,790 metres).*



Type: Fresh (<200 mg/L Cl)
Depth: 0-150 m (FFM02)
Origin: Meteoric recharge
Reactions: Weathering; ion exchange; possible dissolution of calcite; redox and microbial reactions
Redox: Oxidising-reducing

Type: Mixed Brackish (200-2000 mg/L Cl)
Depth: 50-150 m (FFM02)
Origin: Mixture of meteoric and Littorina/Baltic Sea water

Type: Brackish Marine (2000-6000 mg/L Cl)
Depth: 50-200 m (FFM01/FFM02)
Origin: Littorina + Last Deglaciation ± Saline
Reactions: Water/rock interaction; ion exchange; possible precipitation of calcite; redox and microbial reactions
Redox: Mostly reducing

Type: Saline (10 000-20 000 mg/L Cl)
Depth: ~800 to at least 1000 m (FFM01)
Origin: Saline ± Old Glacial/Last Deglaciation + deeper highly saline component
Reactions: Water/rock interaction; ion exchange; microbial reactions
Redox: Reducing

Type: Brackish Non-marine (4000-10 000 mg/L Cl)
Depth: 200- ~800 m (FFM01)
Origin: Old Meteoric ± Old Glacial/Last Deglaciation + Saline
Reactions: Water/rock interaction; ion exchange; possible precpititation of calcite; redox and microbial reactions
Redox: Reducing

Note: Transition compositions occur between the Brackish Marine and Brackish Non-marine groundwater types over varying depth intervals; this may reflect natural or anthropogenic mixing

Samples from restricted borrhole section lengths (<20 m)

Samples from long borehole section lengths (150-300 m)

Open single fractures

All elevations are in metres RHB 70

Recharge flow is dominantly near-surface and horizontal towards the NE.
Groundwater flow is restricted to the upper 200-300 m of the bedrock characterised by a network of mostly subhorizontal, open, intersecting single fractures. Influence is weak to ~500 m depth and very low to non-existent at greater depths.

Figure 7-17. *ENE-WSW 2D cross-section through the target volume showing the groundwater types and their properties (salinity, origin, major reactions and redox conditions). Fracture domains FFM01 and FFM02, comprising the footwall, are indicated. Dashed lines in the upper bedrock are only illustrative of the general gently dipping to subhorizontal fractures commonly present. The dotted lines in different colours crossing the section represent the approximate depths of penetration of (or extrapolation of) the different groundwater types along hydraulically-active deformation zones. (Cross-section length = 2,975 metres).*

8 Uncertainties

The area covered by 'Explorative analysis', documented as 'Appendix 1' to all previous level II reports, covers all the uncertainties referred to below. The three key issues normally addressed are: a) Data Quality Control, b) Hydrogeochemical Evaluation of the data, and c) Conceptualisation and Visualisation of the data based on the outcome of point (b). Uncertainties associated with issues (a) and (b) can be subdivided into those that can be addressed quantitatively and those at a more qualitative level. Expert judgement plays a major role in issue (c) and therefore uncertainties can only be assessed qualitatively, although it can be argued that expert judgement is made based on a quantitative input from issues (a) and (b). Many of the qualitatively-based uncertainties can not be allocated a ± % uncertainty error judgement, but the product (e.g. a concept or a visualisation) can be judged 'reliable' if it is made on a systematic and iterative approach based on quantitative data.

8.1 Groundwater data quality control

Groundwater Data Quality Control plays such a major part in the overall integrity of the hydrogeochemical programme that much effort has been devoted to this end. Two approaches have been used: 1) Data Freezes 1.2, 2.1 and 2.2 were based on a judgement of sample 'Representativeness' classified on a 1-3 class basis, i.e. Good, Intermediate and Poor, and 2) Data Freeze 2.3 was based on a system of categorisation into 5 different groundwater types whereupon the previous Class 1 was subdivided into Categories 1 and 2, Class 2 into Categories 3 and 4, and Class 3 into Category 5. This change in approach was based on two issues resulting from the Laxemar-Simpevarp area investigations: a) for several reasons the quality of much of the groundwater data did not reach required standards, and b) to increase the sensitivity of the data set to meet the requirements of the HydroNet modelling group.

Producing a quality-based data set has, by necessity, been a dynamic process with the implementation of changes with each new data freeze as new data (or modified data) have become available. Thus, on many occasions, data previously judged to be representative had to be downgraded and/or data considered inadequate (e.g. lacking isotopes or incomplete sampling) were upgraded.

Four groups of water samples have been involved in the hydrogeochemical programme: a) precipitation, b) surface waters (lake, stream and Baltic Sea), c) near-surface groundwaters (soil pipe, percussion boreholes), and d) deep groundwaters (cored boreholes). Precipitation samples have not undergone any representativity check *senso stricto* due to disturbances such as unpredictable annual and seasonal trends and possible evaporation effects. These samples have simply been designated as 'intermediate quality' and subdivided into those with complete environmental isotope values (considered the most important input) and those which lack such data. Consequently the major uncertainty that has been addressed is the analytical uncertainty (see below).

For lake and stream surface waters and shallow, near-surface groundwaters (soil pipe), the complex nature of the environment being sampled limits the degree to which these environments can be evaluated. In common with the precipitation samples, these have been designated as 'intermediate quality' with subdivisions based on a cut off charge balance of ±10% (due their more dilute character) and the presence or absence of the most important major ions and environmental isotopes. The Baltic Sea samples are treated likewise with the added requirements of using a lower cut-off charge balance of ±5% and only considering those waters with a chlorinity range of 2,500–2,800 mg/L. This range was chosen to exclude samples potentially influenced (i.e. diluted/contaminated) by coastal run-off waters. Once again, the major uncertainty that has been addressed is the analytical uncertainty (see below).

For the percussion and cored borehole near-surface to deep groundwaters, all samples have been given a rigorous quality judgement based on many different parameters individually and systematically addressed for each sampled borehole section.

8.1.1 Analytical uncertainties

These can be quantitatively judged for all input analytical data (including charge balance) and have been presented as a ± % uncertainty precision error /Nilsson 2008/. Some problems have been encountered with the reliability of bromide analysis, and tritium has been analysed at different detection levels during different time periods, in both cases increasing the analytical uncertainties. Where applicable, these uncertainties are noted when such data are being described and discussed.

8.1.2 Drilling water content

An important indication of sample quality is reflected in drilling water contents in excess of 1%. This cut-off contamination limit is historically based on earlier SKB site investigation programmes. An integral part of the groundwater quality classification is therefore based on the amount of drilling water present, and different percentage ranges have been used to indicate the degree of representativeness or to categorise each sample. The impact of drilling water and the percentage ranges used are documented in the earlier Background Reports, and this report sections 4.1.1 and 4.1.2, and the percentage ranges more recently in the Excel sheet 'Explanation Folder' accompanying the F.2.2, 2.3 data set.

8.1.3 Borehole activities

These activities include everything from the actual drilling (i.e. water budget – drilling water in drilling water out), to borehole cleaning, to hydraulic and geophysical logging, to periods of open hole inactivity, to groundwater sampling (e.g. Tube sampling versus packed-off section sampling). All of the mentioned can result in contamination of the sampled groundwater, not only quantitatively from the spiked drilling water contents, but qualitatively from the mixing of introduced formation groundwaters from higher and/or lower bedrock levels (e.g. by short-circuiting the hydraulic system). Tritiated groundwaters at dubious depths can indicate mixing of the near-surface groundwater sources and higher salinities than expected can indicate mixing with deeper-derived groundwaters. By systematically addressing these possibilities for each borehole, based on geology (e.g. single hole interpretations), hydrogeology (e.g. borehole flow directions, transmissivity and electrical conductivity logs) and what would be expected hydrochemically, the reliability or otherwise of each sample can be semi-quantitatively assessed and the degree of uncertainty either increased or reduced accordingly. This systematic and iterative approach is fully documented for each percussion borehole and each cored borehole and sampled section (see Appendix A and B).

8.1.4 Monitoring borehole sections

The reliability and quality of analytical data derived from the monitoring boreholes have been influenced negatively by a lack of time series measurements, and contamination by uranine (and to a lesser extent caesium) resulting from the hydraulic tracer test programme. In both cases uncertainties have been introduced; in the former whether the sample has achieved hydrochemical stability and is therefore representative, and in the latter the anthropogenic increase of uranine may be incorrectly interpreted as an artefact of the introduced uranine during initial drilling of the boreholes, and anomalous increases in caesium may be misinterpreted. The relevant monitoring boreholes have been documented (cf. Table 4-6, section 4.2.3) and the relevant categories adjusted to accommodate these uncertainties.

8.1.5 Other anthropogenic influences

Tritium contamination resulting directly from leakage of tritiated water from the downhole equipment, and possibly indirectly from the cooling water outlet close to the nuclear facility, is suspected in several boreholes. In the latter case perturbations caused by large- and small-scale hydraulic pump tests (and tracer tests) may have facilitated the dispersion of tritium contamination in the Forsmark area, and also contributed to anomalous redistributions of bomb-produced tritium and, in some cases, also ^{14}C. The relevant monitoring boreholes have been documented and the relevant categories adjusted to accommodate these uncertainties.

8.2 Hydrogeochemical evaluation

Much of hydrogeochemical evaluation (i.e. explorative analysis) presented in this report is based largely on various types of x-y plots:

- Elevation-ion/isotope/ion ratio plots
- Ion-ion plots
- Ion-isotope plots
- Ion-ion ratio plots
- Isotope-ion ratio plots
- Isotope-isotope plots
- Ion ratio-ion ratio plots

Strictly these plots should be presented showing the analytical error bars on each sample point and, in the case of elevation, theoretically an error bar relating to the uncertainty of the depth measurement which is very small. This has not been routinely done because in many cases the error bars interfere with the main illustrative objectives of the plots. To compensate for this, some examples of plots are presented below selected to cover the variation in uncertainties of the most commonly used major ions and isotopes. For specific, more exotic constituents plotted (e.g. ^{36}Cl), the analytical uncertainties are indicated directly on the plots in the report.

For illustrated purposes, therefore, examples are presented below representing: a) uncertainties of ±5% for calcium and sodium (Figure 8-1), and b) uncertainties of ±5% for chloride and ±2% for $\delta^{18}O$ (Figure 8-2).

8.3 Conceptualisation and visualisation

Under this heading is included: a) the modification of the post-glacial scenario which has had a central role since the initiation of the present hydrogeochemical investigations, b) the development of a new conceptualisation/visualisation of the palaeohydrochemical evolution of the Forsmark area from before the last deglaciation time to the present, and c) a modified and updated conceptualisation/visualisation of the Forsmark candidate area using two cross-sections to integrate geology, hydrogeology and hydrochemistry (i.e. both groundwater and porewater).

Common to all three approaches is a basic understanding of the origin and evolution of the groundwater types and their interrelationship with the geology and hydrology of the Forsmark area. This understanding is the culmination of not only what has been addressed over the past four years in /SKB 2005, SKB 2007/, but also draws on the contributions of the other ChemNet participants who have arrived at largely similar conceptual conclusions based on different groundwater modelling approaches. Moreover, the conclusions reached are generally in accordance with the presently accepted hydrogeological models.

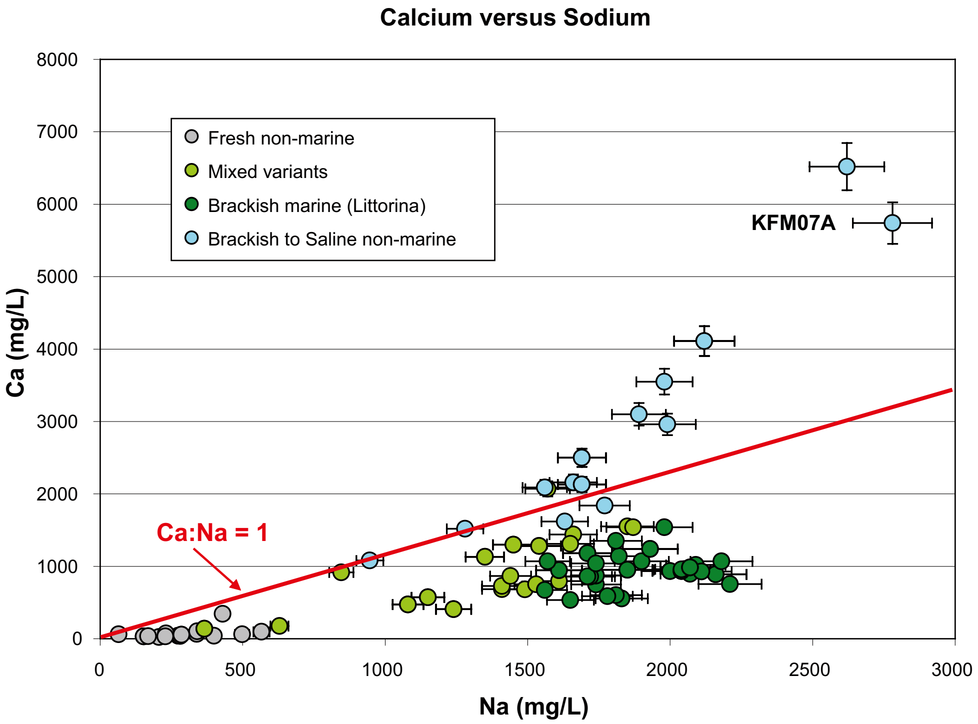


Figure 8-1. *Calcium versus sodium with a typical analytical error of ±5%.*

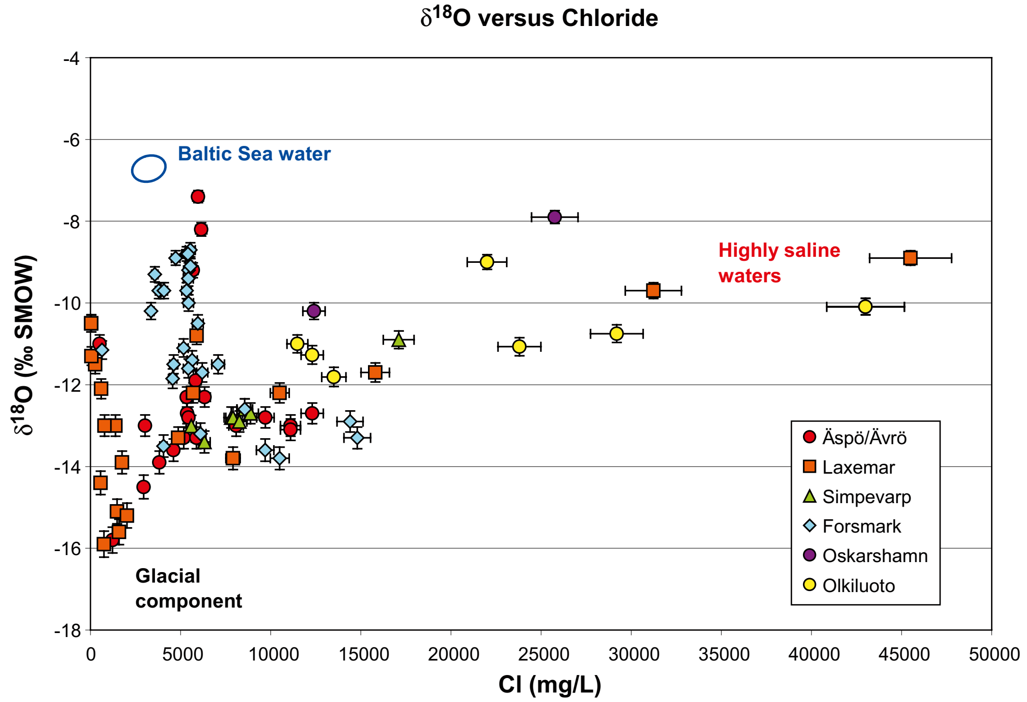


Figure 8-2. *$\delta^{18}O$ versus Cl with an analytical error of ±5% for Cl and ±2% for $\delta^{18}O$.*

8.3.1 Forsmark local scale visualisation

This visualisation is based on a systematic, step-wise approach to determine depth trends and hydrochemical groupings of the groundwater and porewater types as detailed in Chapter 7. Understanding of the system therefore reflects the interpretation of hydrochemical data which has undergone a rigorous quality check and categorisation; in other words a high degree of confidence. Coupled with the results of quality assured hydrogeological measurements and modelling, which in turn is based on geological models of high standard, the input ingredients to the hydrogeochemical visualisation should represent the best quality available at this moment of time. Uncertainties undoubtedly still remain, perhaps stemming from inadequacies in the geological model which may impact on the hydrogeological interpretation and possibly therefore on the integrity of the hydrogeochemical model and visualisation. However, the close agreement between all three disciplines indicates that the degree of uncertainty associated with the input data to the visualisation is low.

The upper 300–700 m of bedrock are fairly well characterised with corresponding low uncertainties. The main uncertainties are associated with the spatial lack of hydrochemical data, both laterally (particularly in the case of the porewater), and at depths greater than 700 m (particularly in the case of the fracture groundwater), such that a large degree of expert judgement has been used to extrapolate the hydrochemistry along the extent of the cross-sections. There is, however, a greater geological and hydrogeological coverage documented to depth, in particular the latter, which has helped to extrapolate the hydrochemistry and porewater data, therefore reducing the uncertainties. Moreover, the uncertainties were further reduced with the realisation that at depths greater than 700 m, the fracture groundwater and porewater chemistries increase fairly uniformly in salinity and laterally appear to be quite homogeneous.

8.3.2 Palaeohydrogeochemical conceptualisation of the Forsmark region

Based on an understanding of the climatic changes that have occurred since the last deglaciation, it is logical to presume that there must have been at that time old meteoric waters comprising components derived from both temperate and cold climate events. These would have mixed gradually with deeper, more saline groundwaters, probably of mixed origin but without a clear residual marine signature remaining. This situation seems to be still valid for the most isolated parts in the bedrock, for example, in low transmissive fractures within the footwall bedrock (fracture domain FFM01) represented by boreholes KFM01D and KFM08D, and in parts of the rock matrix, where such water mixtures remain and have been sampled. This has expanded the scope of the palaeohydrogeochemical (and palaeohydrogeological) conceptualisation of the Forsmark site and thereby decreasing the uncertainty surrounding the boundary condtions used for modelling purposes.

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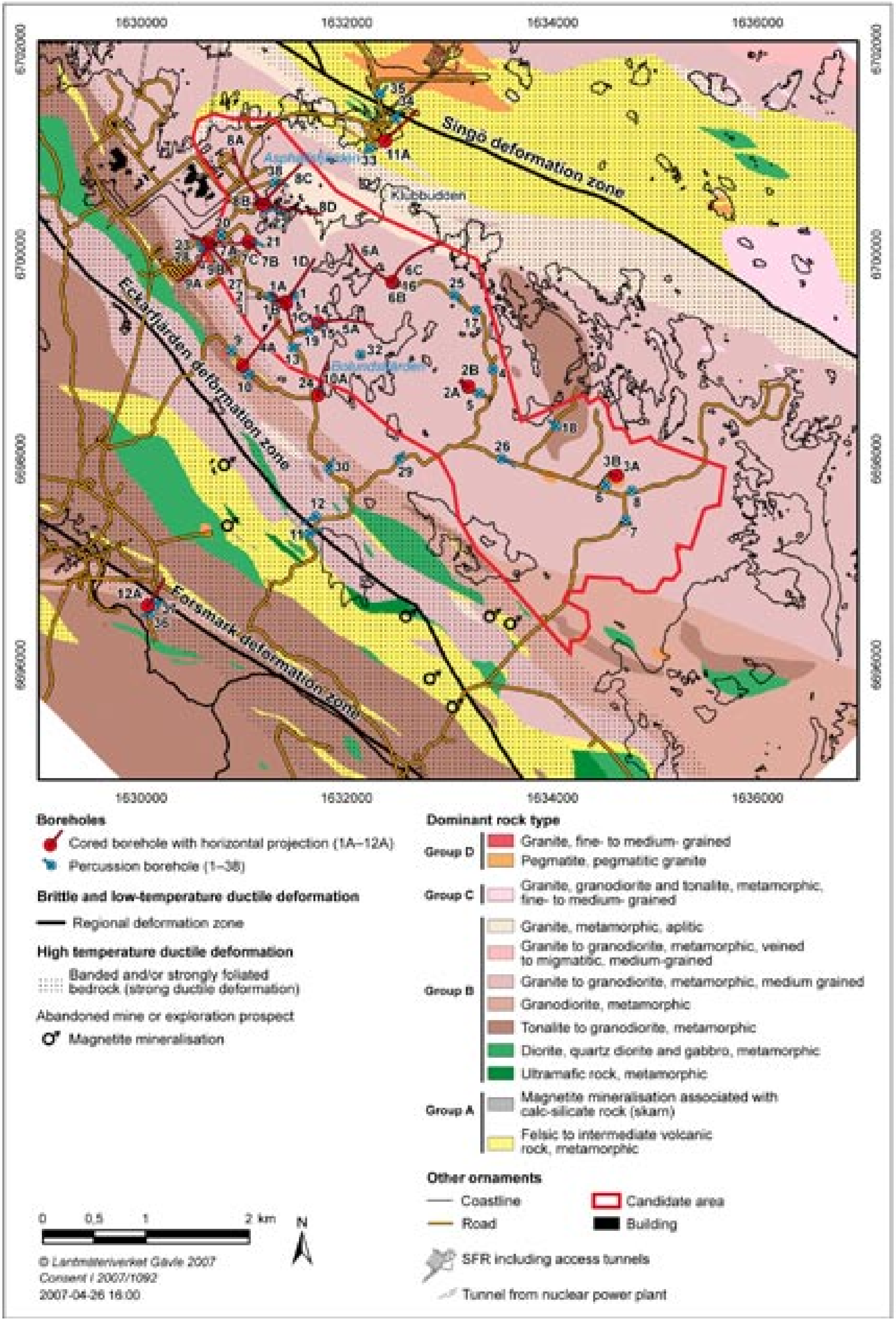
Appendix A

(Percussion boreholes)

Documentation related to categorisation of the stage 2.3 extended dataset groundwater samples. Details of the approach are given in Chapter 4 of this report, and earlier documentation is outlined in SKB R-05-17.

Documentation of the percussion boreholes is presented in tabular form showing the major category criteria that characterise the groundwater chemistry from each sampled borehole length or isolated borehole section.


1630000
1632000
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6702000
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6698000
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Singö deformation zone
Eckarfjärden deformation zone
Forsmark deformation zone
Asphällsfjärden
Klubbudden
Bolundsfjärden
35
34
33
11A
8A
38
8C
8B
8D
20
22
23
21
7C
7B
1D
6A
6C
6B
16
25
9A
27
1A
1B
1C
14
15
5A
17
19
13
32
4A
2B
2A
5
18
10
24
10A
26
3B
3A
6
8
7
30
29
12
11
12A
36
Boreholes
Cored borehole with horizontal projection (1A–12A)
Percussion borehole (1–38)
Brittle and low-temperature ductile deformation
Regional deformation zone
High temperature ductile deformation
Banded and/or strongly foliated bedrock (strong ductile deformation)
Abandoned mine or exploration prospect
Magnetite mineralisation
Dominant rock type
Group D
Granite, fine- to medium- grained
Pegmatite, pegmatitic granite
Group C
Granite, granodiorite and tonalite, metamorphic, fine- to medium- grained
Group B
Granite, metamorphic, aplitic
Granite to granodiorite, metamorphic, veined to migmatitic, medium-grained
Granite to granodiorite, metamorphic, medium grained
Granodiorite, metamorphic
Tonalite to granodiorite, metamorphic
Diorite, quartz diorite and gabbro, metamorphic
Ultramafic rock, metamorphic
Group A
Magnetite mineralisation associated with calc-silicate rock (skarn)
Felsic to intermediate volcanic rock, metamorphic
Other ornaments
Coastline
Road
Candidate area
Building
SFR including access tunnels
Tunnel from nuclear power plant
0
0,5
1
2 km
N
© Lantmäteriverket Gävle 2007
Consent I 2007/1092
2007-04-26 16.00

HFM01 (31.93–200.20 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					x
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					x
Time series/monitoring (inadequate)					
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete: 2nd sampling)					x
Environmental isotopes (incomplete: 1st sampling)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM01 (31.93–71.00; mid. vertical elevation: –36.50 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)			x		
Flow log available			x		
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)			x		
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)					
Major ions (incomplete)			x		
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM01 (33.50–45.50 m; mid. vertical elevation: –37.02 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)			x		
Flow log available			x		
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)			x		
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM02 (25.40–100.10 m; mid. vertical elevation: –59.64 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					x
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM02 (38.00–48.00 m; mid. vertical elevation: –36.50 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)			x		
Flow log available			x		
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)			x		
Time series/monitoring (inadequate)					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					
Monitoring borehole sections			x		
Hydraulic effects (short-circuiting)					

HFM03 (13.10–26.00 m; mid. vertical elevation: –18.10 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)				x	
Flow log available				x	
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)				x	
Charge balance ±5% (±10% for < 50 mg/L Cl)					
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM04 (30.00–221.70 m; mid. vertical elevation: –121.32 m)

Percussion Boreholes					
Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					x
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM04 (58.00–66.00 m; mid. vertical elevation: –57.91 m)

Percussion Boreholes					
Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available	x				
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)	x				
Time series/monitoring (inadequate)					
Charge balance ±5% (±10% for < 50 mg/L Cl)	x				
Major ions (complete)	x				
Major ions (incomplete)					
Environmental isotopes (complete)	x				
Environmental isotopes (incomplete)					
Monitoring borehole sections	x				
Hydraulic effects (short-circuiting)					

HFM05 (0–210.00 m; mid. vertical elevation: –144.60 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available				x	
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)				x	
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM05 (25–210.00 m; mid. vertical elevation: –153.25 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available				x	
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)				x	
Time series/monitoring (inadequate)					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM06 (12.0–110.70 m; mid. vertical elevation: –63.00 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available				x	
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)				x	
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM08 (18.00–93.00 m; mid. vertical elevation: –82.40 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available				x	
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)				x	
Time series/monitoring (inadequate)					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM08 (18.00–143.50 m; mid. vertical elevation: –130.40 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available			x		
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)			x		
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)					
Major ions (incomplete)			x		
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM09 (17.02–50.20 m; mid. vertical elevation: –18.50 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)		x			
Flow log available		x			
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)		x			
Time series/monitoring (inadequate)					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)					
Major ions (incomplete)		x			
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM10 (11.80–150.00 m; mid. vertical elevation: –104.60 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available			x		
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)			x		
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)					
Major ions (incomplete)			x		
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM11 (11.90–182.35 m; mid. vertical elevation: –63.27 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					x
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM12 (14.90–209.55 m; mid. vertical elevation: –78.00 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available				x	
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)				x	
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM13 (14.90–175.60 m; mid. vertical elevation: –77.38 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					x
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM13 (159.00–173.00 m; mid. vertical elevation: –140.00 m)

Percussion Boreholes					
Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)	x				
Flow log available	x				
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)	x				
Time series/monitoring (inadequate)					
Charge balance ±5% (±10% for < 50 mg/L Cl)	x				
Major ions (complete)	x				
Major ions (incomplete)					
Environmental isotopes (complete)	x				
Environmental isotopes (incomplete)					
Monitoring borehole sections	x				
Hydraulic effects (short-circuiting)					

HFM14 (6.00–150.50 m; mid. vertical elevation: –64.86 m)

Percussion Boreholes					
Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM14 (0–150 m; mid. vertical elevation: –62.22 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM15 (6.00–199.50 m; mid. vertical elevation: –0.29 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					x
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM15 (85.00–95.00 m; mid. vertical elevation: –59.05 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					x
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					x
Time series/monitoring (inadequate)					
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					x
Major ions (incomplete)					
Environmental isotopes (complete)					x
Environmental isotopes (incomplete)					
Monitoring borehole sections					x
Hydraulic effects (short-circuiting)					

HFM16 (12.02–132.50 m; mid. vertical elevation: –68.93 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					x
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					x
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM16 (54.00–67.00 m; mid. vertical elevation: –57.19 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)			x		
Flow log available			x		
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)			x		
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					
Monitoring borehole sections			x		
Hydraulic effects (short-circuiting)					

HFM17 (8.00–202.65 m; mid. vertical elevation: –27.40 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available				x	
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)				x	
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)					
Environmental isotopes (incomplete)				x	
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM18 (9.00–173.20 m; mid. vertical elevation: –30.90 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available				x	
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)				x	
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)					
Environmental isotopes (incomplete)				x	
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM19 (168.00–182.00 m; mid. vertical elevation: –137.10 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)	x				
Flow log available	x				
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)	x				
Time series/monitoring (inadequate)					
Charge balance ±5% (±10% for < 50 mg/L Cl)	x				
Major ions (complete)	x				
Major ions (incomplete)					
Environmental isotopes (complete)	x				
Environmental isotopes (incomplete)					
Monitoring borehole sections	x				
Hydraulic effects (short-circuiting)					

HFM20 (12.00–301.00 m; mid. vertical elevation: –153.32 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–300m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					x
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM21 (12.03–200.00 m; mid. vertical elevation: –102.20 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					x
Time series/monitoring (inadequate)					
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					x
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM21 (22.00–32.00 m; mid. vertical elevation: –18.82 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)			x		
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)			x		
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM22 (12.00–221.00 m; mid. vertical elevation: –50.00 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available				x	
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)				x	
Time series/monitoring (inadequate)					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM23 (0.00–211.50 m; mid. vertical elevation: –66.11 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM24 (0.00–151.40 m; mid. vertical elevation: –61.48 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM24 (18.03–151.35 m; mid. vertical elevation: –25.10 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available			x		
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)			x		
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)					
Major ions (incomplete)			x		
Environmental isotopes (complete)					
Environmental isotopes (incomplete)			x		
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM25 (0.00–187.50 m; mid. vertical elevation: –61.48 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM26 (0.00–202.70 m; mid. vertical elevation: –74.37 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM27 (0.00–127.50 m; mid. vertical elevation: –56.38 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					x
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM27 (46.00–58.00 m; mid. vertical elevation: –45.60 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)			x		
Flow log available			x		
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)			x		
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)					
Environmental isotopes (incomplete)			x		
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM28 (0.00–151.20 m; mid. vertical elevation: –70.65 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM29 (0.00–199.70 m; mid. vertical elevation: –84.10 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM32 (0.00-25.00 m; mid. vertical elevation: –11.50 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					x
Flow log available					x
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM32 (26.00–31.00 m; mid. vertical elevation: –30.00 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)		x			
Flow log available		x			
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)		x			
Time series/monitoring (inadequate)					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)					
Environmental isotopes (incomplete)		x			
Monitoring borehole sections		x			
Hydraulic effects (short-circuiting)					

HFM32 (32.00–97.00 m; mid. vertical elevation: –63.24 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)				x	
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)				x	
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)					
Environmental isotopes (incomplete)				x	
Monitoring borehole sections					
Hydraulic effects (short-circuiting)				x?	

HFM32 (50.00–202.65 m; mid. vertical elevation: –99.53 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM32 (50.00–202.65 m; mid. vertical elevation: –124.02 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM32 (98.00–203.00 m; mid. vertical elevation: –147.68 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)				x	
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)				x	
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)					
Environmental isotopes (incomplete)				x	
Monitoring borehole sections					
Hydraulic effects (short-circuiting)				x?	

HFM33 (0.00–140.20 m; mid. vertical elevation: –107.50 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available			x		
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)			x		
Time series/monitoring (inadequate)					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)					
Major ions (incomplete)			x		
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM34 (0.00–200.75 m; mid. vertical elevation: –82.92 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM35 (0.00–200.75 m; mid. vertical elevation: –78.24 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM36 (0.00–140.20 m; mid. vertical elevation: –39.00 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available				x	
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)				x	
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)					
Environmental isotopes (incomplete)				x	
Monitoring borehole sections					
Hydraulic effects (short-circuiting)				x?	

HFM36 (0.00–152.55 m; mid. vertical elevation: –39.00 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available				x	
Without flow log (0–100m)					
Without flow log (0–200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)				x	
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

HFM37 (0.00–191.75 m; mid. vertical elevation: –74.10 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available					
Without flow log (0–100m)					
Without flow log (0–200m)					x
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)					x
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					x?

HFM38 (0.00–200.75 m; mid. vertical elevation: –74.85 m)

Percussion Boreholes

Category	*1*	*2*	*3*	*4*	*5*
Short restricted section length (e.g. monitoring)					
Flow log available				x	
Without flow log (0-100m)					
Without flow log (0-200m)					
Time series/monitoring (adequate)					
Time series/monitoring (inadequate)				x	
Charge balance ±5% (±10% for <50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)					
Environmental isotopes (incomplete)				x	
Monitoring borehole sections					
Hydraulic effects (short-circuiting)					

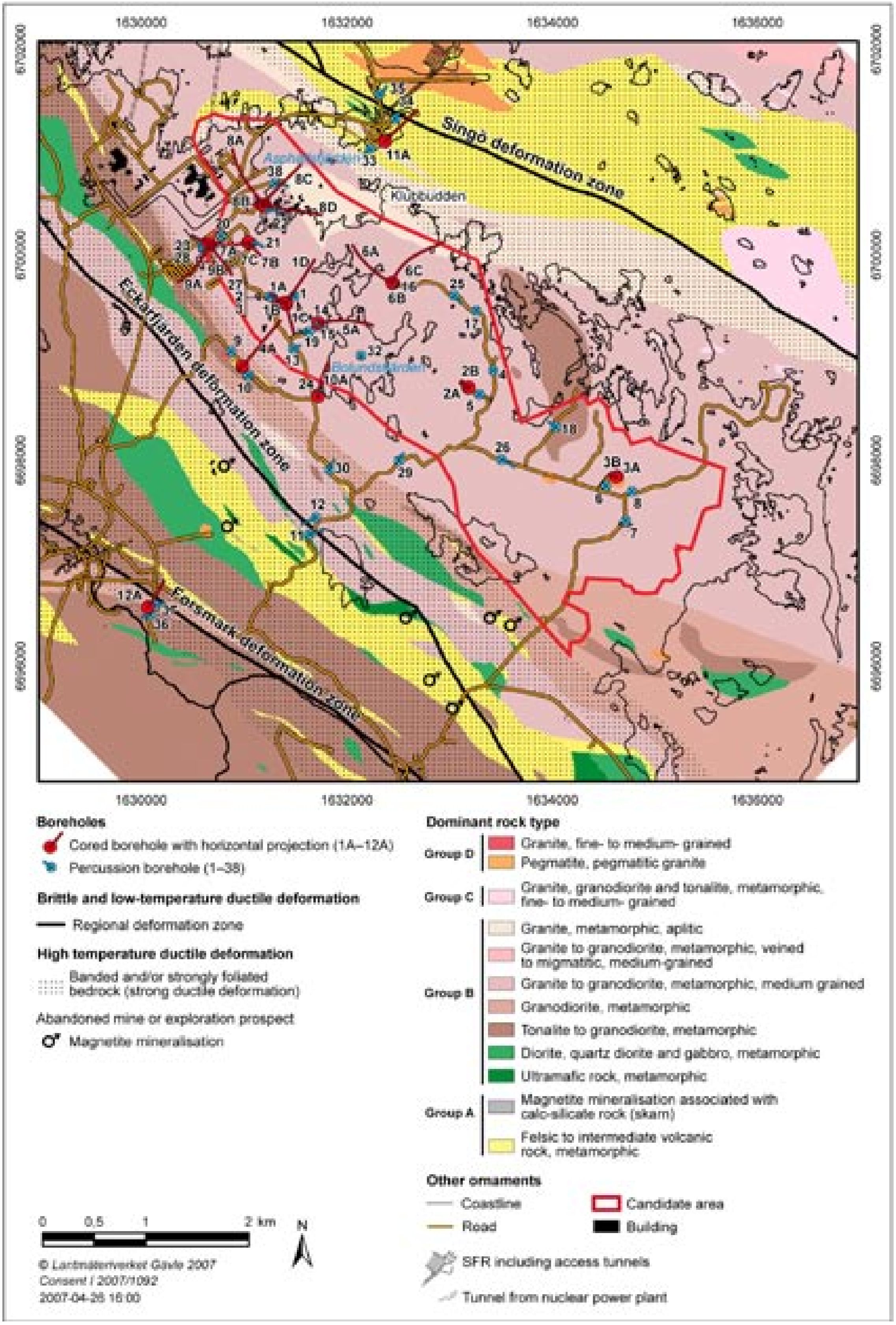
Appendix B

(Cored boreholes)

Documentation related to the categorisation of the stage 2.3 extended dataset groundwater samples. Details of the approach are given in Chapter 4 of this report, and earlier documentation is outlined in SKB R-05-17.

The cored borehole documentation includes the groundwater category tables for each sampled borehole section accompanied by a brief description of: a) the hydraulic character of the borehole and the packed-off sections sampled, b) the hydrochemistry of the drilling water, c) the major ion and isotope chemistry of the sampled groundwaters, and c) the main reasons to the different categories selected.

Unless otherwise stated, all metric reference to the depth, length and sampling location along the boreholes is in 'borehole length' and not vertical depth.


1630000
1632000
1634000
1636000
6702000
6700000
6698000
6696000
Singö deformation zone
Eckarfjärden deformation zone
Forsmark deformation zone
Asphällsfjärden
Klubbudden
Bolundsfjärden
1A
1B
1C
1D
2A
2B
3A
3B
4A
5A
6A
6B
6C
7A
7B
7C
8A
8B
8C
8D
9A
10A
11A
12A
Boreholes
Cored borehole with horizontal projection (1A–12A)
Percussion borehole (1–38)
Brittle and low-temperature ductile deformation
Regional deformation zone
High temperature ductile deformation
Banded and/or strongly foliated bedrock (strong ductile deformation)
Abandoned mine or exploration prospect
Magnetite mineralisation
Dominant rock type
Group D
Granite, fine- to medium- grained
Pegmatite, pegmatitic granite
Group C
Granite, granodiorite and tonalite, metamorphic, fine- to medium- grained
Group B
Granite, metamorphic, aplitic
Granite to granodiorite, metamorphic, veined to migmatitic, medium-grained
Granite to granodiorite, metamorphic, medium grained
Granodiorite, metamorphic
Tonalite to granodiorite, metamorphic
Diorite, quartz diorite and gabbro, metamorphic
Ultramafic rock, metamorphic
Group A
Magnetite mineralisation associated with calc-silicate rock (skarn)
Felsic to intermediate volcanic rock, metamorphic
Other ornaments
Coastline
Road
Candidate area
Building
SFR including access tunnels
Tunnel from nuclear power plant
0 0.5 1 2 km
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Consent I 2007/1092
2007-04-26 16:00

KFM01A (0–100.57 m)

Borehole KFM01A was the first deep borehole to be drilled at the Forsmark site. It is 1,001.49 m long (vertical depth 985.40 m), cased to 100.3 m and inclined at 85.7° from the horizontal. The borehole was drilled to obtain an initial impression of the bedrock at the candidate site that would help to further plan the hydrochemical investigations. Earlier documentation of groundwater quality is given in R-05-17.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					x
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)					x
Time series (absent)					
Suitable section length					
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					x
Environmental isotopes (incomplete)					

Differential Flow Log: Borehole KFM01A records significant transmissivity values only in the upper 200 m (up to $10^{-7.4}$ m^2/s); values of 10^{-10} to 10^{-9} m^2/s characterise the next 160 m after which to the bottom of the borehole the transmissivity is below detection (< 10^{-10} to 10^{-9} m^2/s). ‘Undisturbed’ flow indicates, with one exception at 150 m, groundwater movement from the surrounding host rock to the borehole. This becomes more accentuated with pumping. The highly transmissive bedrock close to the surface represents the shallow bedrock aquifer which forms an effective hinder to the downward flow of near-surface recharge groundwaters. The total inflow of water into the borehole from this structure, estimated from pumping tests during the drilling, was 1–2 L/min.

Electric Conductivity log: Without pumping there is a rapid increase to a high salinity peak at around 1.6 S/m from 50–150 m, i.e. reflecting the higher transmissivity and equivalent to around 5,000 mg/L Cl. From this depth there is a consistent decrease to very dilute waters (0.45 S/m) which persist from 550 m to the borehole bottom. Pumping serves to bring in more saline water which increases the extent of the high salinity peak from 150 to 190 m depth, and uniformly increases very slightly the salinity of the water along the rest of the borehole. The very dilute water dominating most of the borehole is probably due to the flushing water (borehole HFM01) which contains around 500 mg/L Cl; some may have originated from dilute recharge groundwaters entering the borehole from high up in the bedrock. No hydrochemical logging was carried out in this borehole which might have helped to resolve this issue.

Prior to groundwater sampling, therefore, contamination may be expected along most of the low transmissive borehole length. On the other hand, this may be rapidly removed by prior pumping. In the high saline (density) transmissive horizon from 50–200 m depth some contamination from drilling water may be expected, but prior pumping also may be sufficient to remove most of the effects.

Drilling Water: HFM01 (31.93–71.00 m; major flow input at ~52 m); well constrained major flow input depth. Typical Na-Cl(HCO_3, SO_4) brackish groundwater (530 mg/L Cl) with a ^{18}O signature of around –9.5‰ V-SMOW. Tritium data suggest some younger, near-surface mixing (3.70 TU). Volume of flushing water used during drilling was not recorded. Only 1–2 L/min entered the borehole mostly from 100–200 m borehole length, so it can be assumed that only small amounts of flushing water entered the bedrock during drilling.

Charge Balance: Modelled PHREEQC value of 0.01% OK.

Time Series: Only one sample in 2002-05-25 coinciding with completion of drilling. No time series (1,419.7 mg/L Cl) and no drilling water recorded as it is percussion drilled. A marine component (69.9 mg/L Mg) is present. Major ions incomplete (no HCO3, Fe(tot)/Fe(II), Mn, S^{2-} and DOC/TOC).

Isotopes: Complete; enriched $\delta^{18}O$ (–9.9‰ V-SMOW) and high tritium (5.2 TU) indicating a young, recharge signature and portions of marine groundwater.

Trace elements: Absent.

General: Long sampled section supports the indication of mixed origin groundwaters (recharge + marine components). This, coupled with an absence of time-series data and major ion values, has led to a Category 5 allocation.

References: SKB P-04-05; P-03-28; P-03-94.

KFM01A (110.10–120.77 m; mid. vertical elevation: –111.75 m)

Cored Boreholes	Category				
Aspects/Conditions	1	2	3	4	5
Drilling water (≤ 1%)		x			
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					

Drilling Water: HFM01 (31.93–71.00 m; major flow input at ~52 m); well constrained major flow input depth. Typical Na-Cl(HCO_3, SO_4) brackish groundwater (530 mg/L Cl) with a $\delta^{18}O$ signature of around –9.5‰ V-SMOW. Tritium data suggest some younger, near-surface mixing (3.7 TU). Volume of flushing water used during drilling does not appear to be documented. Only 1–2 L/min entered the borehole mostly from 100–200 m borehole length, so it can be assumed that only small amounts of flushing water entered the bedrock during drilling.

Charge Balance: OK at –1.76%.

Time Series: Sampled from 20030117 to 20030224 (35 day period) – good time series data. Drilling water < 1% after having decreased from 7.73 to 0.87 during the first 3 weeks of sampling. Apart from the initial sample and a later example (3,842 and 4,078 mg/L), chloride has remained stable between 4,494 to 4,567 mg/L. Significant Mg component (142.0 mg/L) supporting a marine influence. Good coverage of major ions.

Isotopes: Complete for selected sample; weakly depleted $\delta^{18}O$ (around –11.50‰ V-SMOW), below detection tritium (< 0.80 TU) and ^{14}C at 13.4 pmC indicating an older groundwater.

Trace elements: Reasonable coverage for the selected sample; absence of heavy trace elements.

General: Na-Ca(Mg)-Cl (SO_4) brackish marine (Littorina) type groundwater with probably a significant glacial component which has both diluted the salinity and maintained a more depleted $\delta^{18}O$ signature than otherwise typical for this groundwater type. Category 2 allocated (absence of heavy trace elements).

KFM01A (109–00–130.00 m; mid. vertical elevation: –115.79 m)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)				?	
Drilling water (≤ 5%)				?	
Drilling water (≤ 10%)				?	
Drilling water (> 10%)				?	
Time series (adequate)				x	
Time series (inadequate)					
Time series (absent)					
Suitable section length				x	
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)				x	
Major ions (incomplete)					
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					

Drilling Water: HFM01 (31.93–71.00 m; major flow input at ~52 m); well constrained major flow input depth. Typical Na-Cl(HCO_3, SO_4) brackish groundwater (530 mg/L Cl) with a $\delta^{18}O$ signature of around –9.5‰ V-SMOW. Tritium data suggest some younger, near-surface mixing (3.7 TU). Volume of flushing water used during drilling does not appear to be documented. Only 1–2 L/min entered the borehole mostly from 100–200 m borehole length, so it can be assumed that only small amounts of flushing water entered the bedrock during drilling.

Charge Balance: OK at –0.53%.

Time Series: Monitoring borehole sampled on four occasions from 2005-06-09 to 2006-10-09 at intervals varying from 4–7 months. Only one drilling water value exists, i.e. 24% from the initial sampling period, but this is due to contamination from hydraulic tracer testing and can be discounted. Salinity has steadily increased during the four sampling occasions from 3,330–4,310 mg/L Cl. This final value (together with the other major ions) is close to the selected sample from the previous level described above (exceptions are higher HCO_3 and SO_4) which covers the same borehole interval sampled. Good coverage of major ions.

Isotopes: Complete for selected sample; compared to the previously described sample $\delta^{18}O$ is more enriched (–10.30‰ V-SMOW); tritium systematically decreases from 1.6–1.0 TU suggesting a systematic removal of drilling water; ^{14}C at 26.57 pmC indicating a mainly post-glacial groundwater in agreement with the previous section already described.

Trace elements: Good coverage.

General: Na-Ca(Mg)-Cl (SO_4) brackish marine (Littorina) type groundwater supported by the enriched $\delta^{18}O$ signatures; there is no suggestion of the depleted $\delta^{18}O$ signatures recorded from the previously described borehole section. The changes in groundwater composition from 2003 (see above-described section) to 2006 with the present monitoring section, suggests a removal of a limited reservoir of brackish marine/glacial type groundwater mixture to be replaced by a more brackish marine which now characterises the sampled borehole section. Category 4 has been allocated because of: a) the persistent presence of tritium, and b) time series instability during sampling.

KFM01A (176.80–1,183.90 m; mid. vertical elevation: –176.27 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)		x			
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					

Drilling Water: HFM01 (31.93–71.00 m; major flow input at ~52 m); well constrained major flow input depth. Typical Na-Cl(HCO_3, SO_4) brackish groundwater (530 mg/L Cl) with a $\delta^{18}O$ signature of around –9.5‰ V-SMOW. Tritium data suggest some younger, near-surface mixing (3.7 TU). Volume of flushing water used during drilling does not appear to be documented. Only 1–2 L/min entered the borehole mostly from 100–200 m borehole length, so it can be assumed that only small amounts of flushing water entered the bedrock during drilling.

Charge Balance: OK at –3.73%.

Time Series: Sampled 2003-03-03 to 2003-03-31 (28 days). Good time series showing a small increase in salinity with sampling time (5,041–5,330 mg/L Cl) accompanied with an increase in Mg (154–204 mg/L). Decrease also in drilling water from 7.26–4.80%. Good coverage of major ions.

Isotopes: Complete for several samples including the selected sample; $\delta^{18}O$ is enriched (consistently around –8.80‰ V-SMOW) with no systematic variations, and tritium is mostly below detection (< 0.8 TU). ^{14}C at 17 pmC indicates an old groundwater similar to level 110.10–120.77 m described above.

Trace elements: Reasonably good coverage; no heavy trace elements.

General: Na-Ca(Mg)-Cl (SO_4) brackish marine (Littorina) type groundwater supported by the enriched $\delta^{18}O$ values. Category 2 allocated because of the drilling water content (1–5%).

KFM01B (34.74–46.24 m; mid. vertical elevation –36.61 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)				?	
Drilling water (≤ 5%)				?	
Drilling water (≤ 10%)				?	
Drilling water (> 10%)				?	
Time series (adequate)				x	
Time series (inadequate)					
Time series (absent)					
Suitable section length				x	
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)				x	
Major ions (incomplete)					
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					

Drilling Water: HFM01 (31.93–71.00 m; major flow input at ~52 m); well constrained major flow input depth. Typical Na-Cl(HCO_3, SO_4) brackish groundwater (530 mg/L Cl) with a $\delta^{18}O$ signature of around –9.5‰ V-SMOW. Tritium data suggest some younger, near-surface mixing (3.7 TU). Volume of flushing water used during drilling does not appear to be documented. Only 1–2 L/min entered the borehole mostly from 100–200 m borehole length, so it can be assumed that only small amounts of flushing water entered the bedrock during drilling.

Charge Balance: OK at –1.67%.

Time Series: Inadequate time series; only one sampling. Fresh water (184 mg/L Cl) with moderate drilling water content (8.5%). Incomplete coverage of major ions; no Fe(tot)/Fe(II), S^{2-} or DOC/TOC.

Isotopes: Complete for single sample; recharge $\delta^{18}O$ values of –11.10‰ V-SMOW supported by tritium at 9.3 TU and ^{14}C at 68.4 pmC.

Trace elements: Poor coverage.

General: Na-HCO_3 fresh groundwater. Probably representative for shallow levels but lack of time series and moderate drilling water content resulted in a Category 4 allocation.

KFM01D (194.00–195.00 m; mid. vertical elevation –155.69 m)

Borehole KFM01D is 800.24 m long (vertical depth of 996.21 m), cased to 91.06 m, inclined at 54.89° from the horizontal and dips to the NE. The borehole was drilled to obtain detailed geological, hydrogeological and hydrochemical information of the target volume.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)			x		
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)					
Time series (absent)			x		
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)					
Major ions (incomplete)			x		
Environmental isotopes (complete)					
Environmental isotopes (incomplete)			x		

Differential Flow Log: Borehole KFM01D records significant transmissivity values mostly in the upper 150 m (maximum to $10^{-5.4}$ m^2/s at almost 150 m); a further more moderate to low transmissivity occurs from around 300–430 m with values ranging from below detection at 10^{-9} to $10^{-6.7}$ m^2/s. The rest of the borehole indicates transmissivities below detection (< 10^{-10} to 10^{-9} m^2/s) apart from 557 m where $10^{-7.9}$ m^2/s is recorded. 'Undisturbed' flow (without pumping) mostly indicates groundwater movement from the bedrock to the borehole; the main exception to this occurs around 150 m where groundwater movement is from the borehole to the surrounding host rock. Pumping indicates without exception movement from the bedrock to the borehole. The highly transmissive bedrock close to the surface represents the shallow bedrock aquifer which forms an effective hinder to the downward flow of near-surface recharge groundwaters. Single hole injection tests indicate that most groundwater inflow occurs in the following sections: 118.6–123.6 m, 303.6–308.6 m and 313.6–318.6 m.

Electric Conductivity log: This was measured both with and without the lower rubber discs; the former are the most relevant and only discussed here. Without pumping there is little variation in salinity along the borehole (around 1.2 S/m), apart from a 'kink' at around 570 m, below which there is a very small decrease in salinity to the borehole bottom. During pumping the pattern changes markedly with: a) an increase in salinity just below the casing to 1.4 S/m (~ 5,000 mg/L Cl) which continues to 140 m, b) a less marked increase in salinity to 1.25 S/m (~ 4,000 mg/L Cl) from 140–430 m, c) an increase to just below 1.4 S/m from 430–570 m, and d) an increase to just over 1.4 S/m from 570-the borehole bottom. Pumping therefore serves to bring in more saline water which increases the higher salinity peak to varying extent along the borehole. One of the interesting observations is the more dilute groundwater indicated between 140–430 m borehole length.

The groundwaters do not appear to have been significantly influenced by the dilute drilling water, which is supported by most of it being recovered during drilling (see below under 'Drilling water'). However, some residual drilling water is to be expected and later sampling of borehole sections at 428 m showed an initial content of around 9% which decreased with sampling to around 3.5%. In contrast, at the 568 m level drilling water contents were initially around 1% and then quickly decreased to < 1%.

The later samples collected in sections at 194.0–195.0 m, 263.8–264.8 m, 354.9–355.9 and 369.0–270.0 m borehole lengths (vertical depths 156, 211, 282 and 293 m respectively), where collected using the sampling equipment for low transmissivity fractures (SLT).

Drilling Water: HFM01 (31.93–71.00 m; major flow input at ~52 m); well constrained major flow input depth. Typical Na-Cl(HCO_3, SO_4) brackish groundwater (530 mg/L Cl) with a ^{18}O signature of around –9.5‰ V-SMOW. Tritium data suggest some younger, near-surface mixing (3.7 TU). Volume of flushing water used during drilling was 772 m^3 with a return of 1,080 m^3; this suggests a signficant yield of water to the borehole from the surrounding bedrock.

Charge Balance: OK at –0.29%.

Time Series: Only one sample in 2006-08-06, i.e. no time series. Groundwater has a salinity of 3,360 mg/L Cl and a drilling water content of 3.85%; a marine component (84.8 mg/L Mg) is present. Major ions incomplete (no Fe(tot)/Fe(II), Mn, S^{2-} or DOC/TOC).

Isotopes: Incomplete; no $\delta^{13}C$ or ^{14}C. Slightly enriched $\delta^{18}O$ (–10.2‰ V-SMOW) and significant tritium (2.4 TU) indicating a young, recharge component.

Trace elements: Absent.

General: Na(Ca, Mg)-Cl(SO_4, HCO_3) brackish marine groundwater type, supported also by the enriched $\delta^{18}O$ component. Negative aspects include an absence of time series, incomplete major and trace element data, the presence of drilling water and tritium suggesting a contaminating young recharge component. On the positive side this is a unique sample from a low transmissive part of the bedrock bridging the gap between higher water-conducting fractures with that of the matrix pore waters. Consequently a Category 3 has been allocated.

References: SKB P-06-161; P-06-227; P-06-195.

KFM01D (263.80–264.80 m; mid. vertical elevation –211.45 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)			x		
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)					
Time series (absent)			x		
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)					
Major ions (incomplete)			x		
Environmental isotopes (complete)					
Environmental isotopes (incomplete)			x		

Drilling Water: HFM01 (31.93–71.00 m); well constrained major flow input depth. Typical Na-Cl(HCO_3, SO_4) brackish groundwater (530 mg/L Cl) with a $\delta^{18}O$ signature of around –9.5‰ V-SMOW. Tritium data suggest some younger, near-surface mixing (3.7 TU). Volume of flushing water used during drilling was 772 m^3 with a return of 1,080 m^3; this suggests a significant yield of water to the borehole from the surrounding bedrock.

Charge Balance: OK at –1.71%.

Time Series: Only one sample in 2006-08-09, i.e. no time series. Groundwater has a salinity of 3,570 mg/L Cl and a drilling water content of 5.25%; a marine component (107 mg/L Mg) is present. Major ions incomplete (no Fe(tot)/Fe(II), Mn, S^{2-} or DOC/TOC).

Isotopes: Incomplete; no $\delta^{13}C$ or ^{14}C. Enriched $\delta^{18}O$ (–9.3‰ V-SMOW) and some tritium (1.9 TU) suggesting a small component of young, recharge water.

Trace elements: Absent.

General: Na(Ca, Mg)-Cl(SO_4, HCO_3) brackish marine groundwater type, supported also by the enriched $\delta^{18}O$ component (more enriched than the previous sample). Negative aspects include an absence of time series, incomplete major and trace element data, the presence of drilling water and tritium suggesting a contaminating young recharge component. On the positive side this is a unique sample from a low transmissive part of the bedrock bridging the gap between higher water-conducting fractures with that of the matrix pore waters. Consequently a Category 3 has been allocated.

KFM01D (314.50–319.50 m; mid. vertical elevation –211.45 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)			x		
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)					
Time series (absent)			x		
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)					
Major ions (incomplete)			x		
Environmental isotopes (complete)					
Environmental isotopes (incomplete)			x		

Drilling Water: HFM01 (31.93–71.00 m; major flow input at ~52 m); well constrained major flow input depth. Typical Na-Cl(HCO_3, SO_4) brackish groundwater (530 mg/L Cl) with a $\delta^{18}O$ signature of around –9.5‰ V-SMOW. Tritium data suggest some younger, near-surface mixing (3.7 TU). Volume of flushing water used during drilling was 772 m^3 with a return of 1,080 m^3; this suggests some small yield of water to the borehole from the surrounding bedrock.

Charge Balance: OK at –1.91%.

Time Series: Only one sample in 2006-08-22, i.e. no time series. Groundwater has a salinity of 3,890 mg/L Cl and a drilling water content of 9%; a marine component (101 mg/L Mg) is present. Major ions incomplete (no Fe(tot)/Fe(II)).

Isotopes: Incomplete; no $\delta^{13}C$ or ^{14}C. Enriched $\delta^{18}O$ (–9.7‰ V-SMOW) and some tritium (1.5 TU) suggesting a small component of young, recharge water.

Trace elements: Good coverage.

General: Na(Ca, Mg)-Cl(SO_4, HCO_3) brackish marine groundwater type, supported also by the enriched $\delta^{18}O$ component (more enriched than the previous sample). Negative aspects include an absence of time series, incomplete major and trace element data, the presence of drilling water and tritium suggesting a contaminating young recharge component. On the positive side this is a unique sample from a low transmissive part of the bedrock bridging the gap between higher water-conducting fractures with that of the matrix pore waters. Consequently a Category 3 has been allocated.

KFM01D (354.90–355.90 m; mid. vertical elevation –282.32 m)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)			x		
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)					
Time series (absent)			x		
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)					
Major ions (incomplete)			x		
Environmental isotopes (complete)					
Environmental isotopes (incomplete)			x		

Drilling Water: HFM01 (31.93–71.00 m; major flow input at ~52 m); well constrained major flow input depth. Typical Na-Cl(HCO_3, SO_4) brackish groundwater (530 mg/L Cl) with a $\delta^{18}O$ signature of around –9.5‰ V-SMOW. Tritium data suggest some younger, near-surface mixing (3.7 TU). Volume of flushing water used during drilling was 772 m^3 with a return of 1,080 m^3, this suggests some small yield of water to the borehole from the surrounding bedrock.

Charge Balance: OK at –1.53%.

Time Series: Only one sample in 2006-08-08, i.e. no time series. Groundwater has a salinity of 3,790 mg/L Cl and a drilling water content of 4.6%; a marine component (106 mg/L Mg) is present. Major ions incomplete (no Fe(tot)/Fe(II), Mn, S^{-2} or DOC/TOC).

Isotopes: Incomplete; no $\delta^{13}C$ or ^{14}C. Enriched $\delta^{18}O$ (–9.7‰ V-SMOW) and some tritium (1.7 TU) suggesting a small component of young, recharge water.

Trace elements: Absent.

General: Na(Ca, Mg)-Cl(SO_4, HCO_3) brackish marine groundwater type, supported also by the enriched $\delta^{18}O$ component (more enriched than the previous sample). Negative aspects include an absence of time series, incomplete major and trace element data, the presence of drilling water and tritium suggesting a contaminating young recharge component. On the positive side this is a unique sample from a low transmissive part of the bedrock bridging the gap between higher water-conducting fractures with that of the matrix pore waters. Consequently a Category 3 has been allocated.

KFM01D (369.00–370.00 m; mid. vertical elevation –293.12 m)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)			x		
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)					
Time series (absent)			x		
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)					
Major ions (incomplete)			x		
Environmental isotopes (complete)					
Environmental isotopes (incomplete)			x		

Drilling Water: HFM01 (31.93–71.00 m; major flow input at ~52 m); well constrained major flow input depth. Typical Na-Cl(HCO_3, SO_4) brackish groundwater (530 mg/L Cl) with a $\delta^{18}O$ signature of around –9.5‰ V-SMOW. Tritium data suggest some younger, near-surface mixing (3.7 TU). Volume of flushing water used during drilling was 772 m^3 with a return of 1,080 m^3; this suggests some small yield of water to the borehole from the surrounding bedrock.

Charge Balance: OK at –1.56%.

Time Series: Only one sample in 2006-08-03, i.e. no time series. Groundwater has a salinity of 4,070 mg/L Cl and a drilling water content of 3.8%; a marine component (117 mg/L Mg) is present. Major ions incomplete (no Fe(tot)/Fe(II), Mn, S^{-2} and DOC/TOC).

Isotopes: Incomplete; no $\delta^{13}C$ or ^{14}C. Enriched $\delta^{18}O$ (–9.7‰ V-SMOW) and some tritium (2.7 TU), the latter suggesting a small component of young, recharge water.

Trace elements: Absent.

General: Na(Ca, Mg)-Cl(SO_4, HCO_3) brackish marine groundwater type, supported also by the enriched $\delta^{18}O$ component (more enriched than the previous sample). Negative aspects include an absence of time series, incomplete major and trace element data, the presence of drilling water and tritium suggesting a contaminating young recharge component. On the positive side this is a unique sample from a low transmissive part of the bedrock bridging the gap between higher water-conducting fractures with that of the matrix pore waters. Consequently a Category 3 has been allocated.

KFM01D (428.50–435.64 m; mid. vertical elevation –340.87 m)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)		x			
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					

Drilling Water: HFM01 (31.93–71.00 m; major flow input at ~52 m); well constrained major flow input depth. Typical Na-Cl(HCO_3, SO_4) brackish groundwater (530 mg/L Cl) with a $\delta^{18}O$ signature of around –9.5‰ V-SMOW. Tritium data suggest some younger, near-surface mixing (3.7 TU). Volume of flushing water used during drilling was 772 m^3 with a return of 1,080 m^3; this suggests some small yield of water to the borehole from the surrounding bedrock.

Charge Balance: OK at –1.71%.

Time Series: Sampled from 2006-06-12 to 2006-07-03 (21 days); salinity showed a small but consistent decrease (5,370–4,940 mg/L Cl) during sampling, reflected also in Na and Ca with corresponding small increases in HCO_3 and SO_4. Magnesium is low (13.7 mg/L) suggesting a non-marine groundwater. Drilling water was variable (3.40–9.20%) but no clear systematic trend. Good coverage of major ions.

Isotopes: Complete; no $\delta^{13}C$ or ^{14}C because of low HCO_3 (21.5 mg/L). Depleted $\delta^{18}O$ (around –11.20‰ V-SMOW) compared to the preceding shallower levels indicating a change in groundwater type; tritium is consistently low (below detection to 1.9 TU) with the chosen sample being under detection (< 0.8 TU).

Trace elements: Good coverage for some of the time series samples.

General: Na-Ca-Cl brackish non-marine type groundwater with a depleted $\delta^{18}O$ signature (compared with the shallower levels) which may indicate a weak cold climate signature. Some suggestion of short-circuiting which seems to be bringing in some weak marine component during the final 4–5 days of sampling. Category 2 allocated because of > 1% drilling water and being able to differentiate a brackish non-marine groundwater type expected to occur at this depth.

KFM01D (568.00–575.14 m; mid. vertical elevation –445.17 m)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)	x				
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)	x				
Time series (inadequate)					
Time series (absent)					
Suitable section length	x				
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)	x				
Major ions (complete)	x				
Major ions (incomplete)					
Environmental isotopes (complete)	x				
Environmental isotopes (incomplete)					

Drilling Water: HFM01 (31.93–71.00 m; major flow input at ~52 m); well constrained major flow input depth. Typical Na-Cl(HCO_3, SO_4) brackish groundwater (530 mg/L Cl) with a $\delta^{18}O$ signature of around –9.5‰ V-SMOW. Tritium data suggest some younger, near-surface mixing (3.70 TU). Volume of flushing water used during drilling was 772 m^3 with a return of 1,080 m^3; this suggests some small yield of water to the borehole from the surrounding bedrock.

Charge Balance: OK at –1.42 to +0.14%.

Time Series: Sampled from 2006-07-13 to 2006-07-30 (17 days); all major parameters showed stability during the sampling period. Drilling water was consistently < 1%.

Isotopes: Complete; no $\delta^{13}C$ or ^{14}C because of low HCO_3 (17.10 mg/L). Somewhat enriched $\delta^{18}O$ (around –10.50‰ V-SMOW) compared to the preceding level; tritium is consistently low (below detection to 1.5 TU) with the chosen sample being under detection (< 0.8 TU).

Trace elements: Good coverage.

General: Ca-Na-Cl brackish non-marine type groundwater with a somewhat enriched $\delta^{18}O$ signature compared with the preceding shallower level; no indication of a marine component. Category 1 allocated because of < 1% drilling water, good time series stability, and all major and most trace elements.

KFM02A (1.00–100.00 m and 18.00–100–40 m; mid. vertical elevation of –42.99 m and –51.67 m respectively)

Borehole KFM02A is 1,002.50 m long (vertical depth of 996.45 m) , cased to 100.40 m, and inclined at 85.40° from the horizontal. The borehole was drilled to obtain an initial impression of the bedrock in the south-east part of the candidate site that would help to further plan the hydrochemical investigations. Some earlier documentation of groundwater quality is given in R-05-17.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)				x	x
Time series (absent)					
Suitable section length					
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	x
Major ions (complete)					
Major ions (incomplete)				x	x
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					x

Differential Flow Log: Borehole KFM02A records significant transmissivity values from 100–300 m (range 10^{-8}–$10^{-4.5}$ m^2/s) and from 410–520 m (range below detection at 10^{-9} to $10^{-5.5}$ m^2/s); to the borehole bottom values were under detection. These high transmissivities correspond to gently-dipping deformation zones ZFM866 and ZFMA3, and ZFMA2 and ZFMF1, respectively. 'Undisturbed' flow (without pumping) mostly indicates groundwater movement from the bedrock to the borehole; the main exception to this occurs in some fractures from 100–230 m where groundwater movement is from the borehole to the surrounding host rock. Pumping indicates without exception movement from the bedrock to the borehole. Single hole injection tests agree with the differential flow log measurements.

Electric Conductivity log: Without pumping the salinity is high (1.45 S/m; ~5,500 mg/L Cl) and quite uniform from 100–520 m, i.e. corresponding to the high transmissive bedrock sections. This is followed by a gradual decrease to around 1 S/m (~ 4,000 mg/L Cl) at around 700 m borehole length whereupon it uniformly continues to the borehole bottom apart from a 'kink' at around 900 m borehole length. During pumping the pattern remains unchanged but the salinity increases to a maximum of 1.65 S/m (~ 6,000 mg/L Cl) in the upper 100–530 m borehole length, and to around 1.1 S/m from 530 m to the bottom of the borehole. Pumping therefore serves to bring in more saline water from the surrounding bedrock which increases the salinity to varying extent along the borehole.

The volume of flushing water consumed during drilling was 1,130 m^3 and the volume of returned water pumped from the borehole during drilling was 2003 m^3, this suggests a substantial yield of water to the borehole from the surrounding bedrock. The effect of drilling water can be seen from the hydrochemical logging of the open borehole carried out some 38 days prior to the differential flow measurements. This logging indicated that following drilling up to 80% drilling water occupied the open borehole from around 600–1,000 m, with 35–50% from around 150–500 m and 10% at the shallowest depths (< 50m). This pattern is probably reflected also in the differential flow measurements described above. Furthermore, without the uranine tag the effect of the drilling water would not be obvious as it contains around 4,000 mg/L Cl and is similar in composition to the groundwater eventually collected.

However, residual drilling water is unwelcome and later sampling of borehole sections at: a) 509–516 m borehole length show an initial 25% drilling water decreasing and evening out at around 6%, b) 505–520 m which show an initial content of around 14% decreasing to around 6%, and c) sections 105.6–126.5 m and 413.5–433.5 m which were consistently under 5%. At 417.0–426.5 m 35–40% of drilling water was initially present.

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 20060911. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) groundwater with a Littorina-type signature (~3,910 mg/L Cl; 180 mg/L Mg) with a δ^{18}O signature of –9.9‰ V-SMOW. A value of δ^{13}C at 34.31 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU). Volume of flushing water used during drilling apparently was not recorded.

Charge Balance: OK at –1.42 to +0.35%.

Time Series: Only one sample from each section in 2002-11-29 and 2003-03-31, i.e. no time series. Groundwaters vary considerably from a fresh water (84.4 mg/L Cl) in 2002 to a brackish groundwater (3,256 mg/L Cl) after a period of 4 months. No drilling water was involved in the percussion drilling of the borehole length sampled. Major ions incomplete (no Fe(tot)/Fe(II), Mn, S^{2-} or DOC/TOC).

Isotopes: Complete for the 2002 sampling (no data for the 2003 sampling). Depleted δ^{18}O (–11.40‰ V-SMOW), a significant tritium (11.2 TU) and δ^{13}C at 86.13 pmC content, all indicate a young, recharge groundwater.

Trace elements: Absent.

General: Na-HCO_3 fresh groundwater type for the 2002 sampling; this is believed to be representative for the upper bedrock. Allocated Category 4 because of incomplete major ion data and the long borehole length sampled (i.e. the water input depth to the borehole is not constrained). The 2003 sample is not representative and the brackish marine groundwater type represented is due to mixing, some anthropogenic, since the 2002 sampling. Allocated Category 5.

References: SKB P-03-34, P-03-48, P-03-53, P-03-95, P-04-40, P-04-70.

KFM02A (106.50–126–50 m; mid. vertical elevation –51.67 m)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)			x		
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)			x		
Time series (absent)					
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)					
Major ions (incomplete)			x		
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 20060911. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) groundwater with a dominant Littorina-type signature (~3,910 mg/L Cl; 180 mg/L Mg) with a δ^{18}O signature of –9.9‰ V-SMOW. A value of δ^{13}C at 34.3 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU). Volume of flushing water used during drilling apparently was not recorded.

Charge Balance: OK at –1.7 to 0.49%.

Time Series: Sampled from 2003-11-07 to 2003-11-18 (11 days); salinity showed a small but consistent increase (584–642 mg/L Cl) during sampling, reflected also in Na and Ca with corresponding small increases in HCO_3 and SO_4. Magnesium is low (31 mg/L) suggesting a non-marine groundwater. Drilling water was consistently under 1%. Good coverage of major ions for the chosen sample but Fe(II) missing.

Isotopes: Complete for the chosen sample. Depleted δ^{18}O (–11.20‰ V-SMOW), below detection tritium (< 0.8 TU) and δ^{13}C at 65.01 pmC.

Trace elements: Reasonable good coverage but heavy metal species missing.

General: Brackish Na-Ca-Cl (HCO_3) non-marine type groundwater with a somewhat depleted δ^{18}O signature typical of recent recharge. Category 3 allocated because of slight instability during sampling; more time series would have been helpful. Fe(II) also missing.

KFM02A (Series taken during drilling: 105.10–159.30 m, 250.00–291.45 m and 248.75–395.88 m (mid. vertical elevation of 124.52 m 262.57 m, 313.96 m respectively)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					x
Time series (adequate)					
Time series (inadequate)					
Time series (absent)					x
Suitable section length					
Sampling during drilling					x
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 20060911. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) groundwater with a dominant Littorina-type signature (~3,910 mg/L Cl; 180 mg/L Mg) with a δ^{18}O signature of –9.9‰ V-SMOW. A value of δ^{13}C at 34.3 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU). Volume of flushing water used during drilling apparently was not recorded.

Charge Balance: OK at –1.51 to –0.10%.

Time Series: One sample taken from each section in 2003-01-20/27/29 (9 days); samples showed a progressive increase in salinity with depth (2,317–3,446 mg/L Cl). Most parameters show a more marked increase in chemistry between the first and second samples, but not as marked between the second and last samples. Drilling water was high in all three samples (20.30–89.00%). Major ions incomplete (no Fe(tot)/Fe(II), Mn, S^{-2} or DOC/TOC).

Isotopes: Absent.

Trace elements: Absent.

General: Brackish mixtures of Na-Ca-Cl (SO_4, HCO_3) all with a strong Littorina component. Problem is an absence of time series, long sampling borehole lengths and an absence of major, trace and isotopic data. Allocated Category 5.

KFM02A (413.50–433.50 m and 411.00–442.00 m; mid. vertical elevation –414.72 m and 417.80 m respectively)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)		x			
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 20060911. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) groundwater with a dominant Littorina-type signature (~3,910 mg/L Cl; 180 mg/L Mg) with a $\delta^{18}O$ signature of –9.9‰ V-SMOW. A value of $\delta^{13}C$ at 34.3 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU). Volume of flushing water used during drilling apparently was not recorded.

Charge Balance: OK at –2.68 to –0.23%.

Time Series: Monitoring borehole samples periodically ranging from 2005-11-07 to 2007-02-14. Salinity shows variable values from 5,370–5,560 mg/L Cl with no obvious time trend, whilst Mg varies from 239–252 mg/L. Drilling water ranges from 3.05–6.64%, also showing no trend. Good coverage of major ions for the chosen sample.

Isotopes: Complete for the chosen sample, otherwise δ^{13}C and ^{14}C missing. Enriched δ^{18}O (around –10.10‰ V-SMOW), below or close to detection tritium (< 0.8 to 1.1 TU), and low ^{14}C at 7.74–10.84 pmC.

Trace elements: Good coverage for the chosen sample.

General: Na-Ca(Mg)-Cl (SO_4) brackish marine (Littorina) groundwater type with a typical enriched δ^{18}O signature. Category 2 allocated because of slight instability during sampling and > 1% drilling water.

KFM02A (490.00–518.00 m; mid. vertical elevation –494.97 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)		x			
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 20060911. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) groundwater with a dominant Littorina-type signature (~3,910 mg/L Cl; 180 mg/L Mg) with a δ^{18}O signature of –9.9‰ V-SMOW. A value of δ^{13}C at 34.3 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU). Volume of flushing water used during drilling apparently was not recorded

Charge Balance: OK at –2.81 to –0.15%.

Time Series: One sample in 2004-02-10 and 2004-02-05 followed by 3 monitoring series samples from 2005-11-04, 2006-06-20 and 2006-10-10; salinity shows a slight increase with time (5,380–5,590 mg/L Cl) whilst Mg is stable around 200 mg/L. Drilling water varies from 2.56–4.87% indicating an increase with time. Good coverage of major ions.

Isotopes: Complete for the chosen sample, otherwise δ^{13}C missing. Enriched δ^{18}O (around –8.87‰ V-SMOW), below to close to detection tritium (< 0.8 to 0.9 TU), and low ^{14}C at 15.89–17.33 pmC.

Trace elements: Good coverage in general.

General: Na-Ca(Mg)-Cl (SO_4) brackish marine (Littorina) groundwater type with a typical enriched δ^{18}O signature. Category 2 allocated because of slight instability during sampling and > 1% drilling water.

KFM02A (509.00–516.08 m; mid. vertical elevation –503.34 m)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)			x		
Drilling water (> 10%)					
Time series (adequate)			x		
Time series (inadequate)					
Time series (absent)					
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 20060911. Typical mixed Na-Ca-Mg-Cl(HCO$_3$, SO$_4$) groundwater with a dominant Littorina-type signature (~3,910 mg/L Cl; 180 mg/L Mg) with a δ^{18}O signature of –9.9‰ V-SMOW. A value of δ^{13}C at 34.3 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU).

Volume of flushing water used during drilling apparently was not recorded.

Charge Balance: OK at –2.99 to –1.97%.

Time Series: Sampled from 2003-09-04 to 2003-10-20 (46 days); salinity shows good stability (reflected by most of the major ions) from 5,420–5,410 mg/L Cl whilst Mg shows a small but consistent decrease from 231–226 mg/L. Drilling water varies from 5.78–7.49% but no relationship with time. Good coverage of major ions.

Isotopes: Only complete for the chosen sample, otherwise sporadic and no satisfactory time series; δ^{13}C, ^{14}C and δ^{18}O often missing. Enriched δ^{18}O (around –8.80‰ V-SMOW), below to close to detection tritium (< 0.8 to 2.4 TU), and low ^{14}C at 17 pmC.

Trace elements: Reasonably good coverage apart from an absence of the heavy metal species.

General: Na-Ca(Mg)-Cl (SO$_4$) brackish marine (Littorina) groundwater type with a typical enriched δ^{18}O signature. Category 3 allocated because of > 5% drilling water and 2.4 TU in the final sample selected. The presence of tritium cannot be explained by the the drilling water component (havng tritium values of 1.3 TU). Instead, anthropogenic contamination is suggested.

KFM02A

Tube samples sampled every 50 m from 150–1,000 m (2003-03-31) are considered unrepresentative and allocated Category 5.

KFM02B (434.00–421.25 m)

Borehole KFM02B is 573.87 m long (vertical depth of 565.505 m), cased to 88.61 m, inclined at 80.27° from the horizontal, and dips to the NW. The borehole was drilled to intersect the gently-dipping ZFM02 and ZFMF1 deformation zones in order to sample a rock matrix pore water profile from ZFMF1 down into the intact bedrock below. The opportunity was taken to sample the groundwaters from ZFMF1.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)				x	
Drilling water (> 10%)					
Time series (adequate)				x	
Time series (inadequate)					
Time series (absent)					
Suitable section length				x	
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)				x	
Major ions (incomplete)					
Environmental isotopes (complete)					
Environmental isotopes (incomplete)				x	

Differential Flow Log: Measurements differentiate two zones of high transmissivity from ~ 90–170 borehole length ($10^{-7.3}$ to $10^{-4.9}$ m^2/s) and from 410–440 m borehole length ($10^{-7.9}$ to $10^{-4.5}$ m^2/s), and two highly transmissive fractures at 470 m ($10^{-4.7}$ m^2/s) and 500 m ($10^{-4.5}$ m^2/s) borehole length. Background borehole values range from 10^{-8} to $10^{-6.8}$ m^2/s. There are no reported single hole hydraulic injection tests.

Electric Conductivity log: Without pumping there is a salinity break at 90–100 m between dilute (~ 0.80 S/m) and more saline water (1.05 S/m). Pumping serves to diminish this break by bringing in more saline at depths shallower than 90 m (i.e. up to 1.05 S/m). At greater depths from around 100 m to near the bottom of the borehole at 585 m, there is very little difference between the salinity with or without pumping, i.e. a steady 1.05 S/m. This underlines a homogeneous mixing in the borehole of fresh recharge groundwaters from shallow depths with typical Littorina-type groundwaters at greater depths from the high transmissive zones.

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 20060911. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) groundwater with a dominant Littorina-type signature (~3,910 mg/L Cl; 180 mg/L Mg) with a $\delta^{18}O$ signature of –9.9‰ V-SMOW. A value of $\delta^{13}C$ at 34.3 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU). Volume of flushing water used during drilling apparently was not recorded.

Charge Balance: OK ranging from –1.90 to –0.38%.

Time Series: 2007-03-21 to 2007-05-14 (3 samples). Inadequate time series but showing a systematic increase in Cl (5,300–5,520 mg/L) over the sampling period of 54 days, accompanied by small decreases in Na and HCO_3 and an increase in Ca. Drilling water is 7.05% but only one measurement. Incomplete major ions (no Fe(tot)/Fe(II), Mn, S^{2-} or DOC/TOC).

Isotopes: Absent.

Trace elements: Absent.

General: Na-Ca-Mg-Cl(SO_4-HCO3) Littorina-type groundwater. Generally shows a small saline instability indicated by the time-series data suggesting the introduction of a slightly deeper component (increase in Cl, SO_4 and Ca) with a decrease in the marine component (possible decease in Mg); more time series data would have been required. Category 4 allocated due to inadequate time series data, an absence of isotope data and incomplete major ion data.

References: SKB P-07-83.

KFM03A (346.65–393.65 m; mid. vertical elevation of –360.78 m)

Borehole KFM03A is 1,001.90 m long (vertical depth of 805.18 m), cased to 102.05 m, and inclined at 85.80° from the horizontal. The borehole was drilled to obtain an initial impression of the bedrock in the south-east part of the candidate site that would help to further plan the hydrochemical investigations. Some earlier documentation of groundwater quality is given in R-05-17.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					x
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)					
Time series (absent)					x
Suitable section length					
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)					
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					x
Environmental isotopes (incomplete)					

Differential Flow Log: Borehole KFM03A records significant transmissivity values from 350–540 m (range 10^{-9}–10^{-4} m^2/s) with individual peaks at around 645 m (to $10^{-5.8}$ m^2/s), at around 810 m (to $10^{-7.9}$ m^2/s) and from 940–1,000 m (range $10^{-6.6}$–10^{-7} m^2/s). The uppermost values partly correspond to the gently-dipping deformation zones ZFMA4 and ZFMA7 at approximately 640 m and 810 m borehole lengths respectively, and ZFMA3 at 810 m borehole length. A possible deformation zone occurs at approximately 945 m. 'Undisturbed' flow (without pumping) mostly indicates groundwater movement from the borehole out into the bedrock; the main exception to this occurs in some individual fractures at around 390 m and 985 m borehole length. Pumping indicates overall flow from the bedrock to the borehole. Single hole injection tests agree generally with the differential flow log measurements.

Electric Conductivity log: This was conducted when the probe was both lowered and raised in the open borehole, and with and without pumping in each case. In addition, the measurements were repeated after an interval of approximately 8 months. The first measurement was made in August 2003. Without pumping the salinity is high (2.6 S/m; ~10,000 mg/L Cl) and quite uniform from 100–640 m. This is followed by a gradual increase over 60 m to 3.5 S/m (~ 13,500 mg/L Cl) at around 700 m borehole length, whereupon it increases uniformly to the borehole bottom where a maximum value of 4 S/m (~ 16,000 mg/L Cl) is reached. There was no difference when the probe was raised or lowered. With pumping the pattern remains unchanged except for a sharper transition to higher salinity at 640 m.

With repeated measurements 8 months later, there was an overall dilution of the borehole water without pumping, especially in the upper 350 m of the borehole where the salinity varied with depth from 0.4–1.7 S/m; this maximum value continued uniformly to around 850 m before gradually increasing to a maximum of 2.8 S/m at the bottom of the borehole. With pumping the more diluted groundwater in the upper 350 m reverted to higher salinity (1.75 S/m) which continued uniformly to 650 m before gradually increasing to a maximum of 2 S/m at the bottom of the borehole.

These observations help to demonstrate the potential changes that can occur in a borehole and its immediate surroundings as a result of drilling, and the subsequent changes which can occur with time under open hole conditions. In this case, after 8 months the uppermost less saline waters had mixed with and diluted the more saline groundwaters to a depth of around 350 m.

Hydrochemical logging was made prior to the differential flow logging and showed that the amount of drilling water in the open borehole varied from around 5–10% for the initial 100–300 m, then increased to a maximum of 53% at 700 m, before decreasing to 10% at around 960 m depth. Although this residual drilling water is unwelcome, later sampling shows that much of this effect is removed during the sampling process, for example: a) sections 386–391 m and 448–453 m borehole length showed under 1% during sampling, b) section 639.0–646.1 m showed a progressive but slight decrease from 5.5–4.2%, and c) section 939.5–946.6 showed a progressive decrease from 13.5–8.3%. In contrast, section 980.0–1,001.2 m showed an increase from 1.5– 4% during sampling.

Drilling Water: HFM06 (12.00–110.70 m; major flow input from ~ 46 m). Typical Na(Ca, Mg)-Cl(HCO_3, SO_4) brackish mixed groundwater type with a weak marine component (1,108 mg/L Cl; 54.5 mg/L Mg) and a $\delta^{18}O$ signature of around –10.60‰ V-SMOW. Tritium is 5.7 TU indicating a modern recharge influence; this is supported by ^{14}C at 61.06 pmC content.

Charge Balance: Inadequate analytical data.

Time Series: Only one sample was analysed in 2003-05-06, i.e. no time series and no Cl data available to assess salinity; 9.7% drilling water content. Major ions incomplete (no Cl, F, Fe(tot)/Fe(II), S^{2-} or TOC).

Isotopes: Complete. Enriched $\delta^{18}O$ (–9.30‰ V-SMOW), under detection tritium (< 0.8 TU) and a 36.33 pmC content.

Trace elements: Absent.

General: Na-Ca (Mg)-Cl (SO_4,HCO_3) probably brackish marine groundwater type similar to that described below. Allocated Category 5 because of a lack of time series data, incomplete major ion data and substantial drilling water content.

References: P-03-96, P-04-19, P-04-108, P-04-189.

KFM03A (386.00–391.00 m; mid. vertical elevation of –376.57 respectively)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)		x			
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)					
Environmental isotopes (incomplete)		x			

Drilling Water: HFM06 (12.00–110.70 m; major flow input from ~ 46 m). Typical Na(Ca, Mg)-Cl(HCO_3, SO_4) brackish mixed groundwater type with a weak marine component (1,108 mg/L Cl; 54.5 mg/L Mg) and a δ^{18}O signature of around –10.60‰ V-SMOW. Tritium is 5.7 TU indicating a modern recharge influence; this is supported by ^{14}C at 61.1 pmC content.

Charge Balance: OK at –2.66 to –2.17%.

Time Series: Sampled from 2003-09-16 to 2003-10-02 (24 days). Good stability for all major ions (e.g. around 5,440 mg/L Cl) and drilling water consistently under 1%. Major ions complete.

Isotopes: Incomplete; only δ^{13}C and ^{14}C for the final sample in the series which indicated 20.2 pmC. Enriched δ^{18}O (–9.20‰ V-SMOW); tritium is below detection (< 0.8 TU) for all samples except the final one which recorded 2 TU.

Trace elements: Absent in all samples apart from the final sample.

General: Na(Ca, Mg)-Cl($SO_{4,}$ HCO_{3},) brackish marine (Littorina) groundwater. Unfortunately the final sample, which has full major, isotope and trace element data, the sudden occurrence of tritium creates a small question mark – modern input or contamination? Consequently the preceding sample has been chosen and, because of the absence of carbon isotoe data, a Category 2 has been allocated.

KFM03A (448.00–453.00 m and 448.50–455.62 m; mid. vertical elevation of –440.79 and –442.35 respectively)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)		x			
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)					
Environmental isotopes (incomplete)		x			

Drilling Water: HFM06 (12.00–110.70 m; major flow input from ~ 46 m). Typical Na(Ca, Mg)-Cl(HCO$_3$, SO$_4$) brackish mixed groundwater type with a weak marine component (1,108 mg/L Cl; 54.5 mg/L Mg) and a δ^{18}O signature of around –10.60‰ V-SMOW. Tritium is 5.7 TU indicating a modern recharge influence; this is supported by ^{14}C at 61.1 pmC content.

Charge Balance: OK at –2.40 to +0.82%.

Time Series: Sampled on two occasions from 2003-10-17 to 2003-10-24 (5 days) and from 2004-04-15 to 2004-04-27 (12 days). Taken together, there is good stability for all major ions (e.g. 5,330–5,440 mg/L Cl) although the second sampling suggests small increases in Na, Ca, Mg and SO$_4$; drilling water is consistently under 1%. Major ions complete although TOC/DOC are sporadic and missing in the second chosen sample.

Isotopes: Incomplete; only δ^{13}C and ^{14}C for the first sampling occasion which indicated ^{14}C at 19.3 pmC. Otherwise, enriched δ^{18}O (around –9.60‰ V-SMOW) and tritium is below detection (< 0.8 TU) is common for all samples.

Trace elements: Absent in the second sampling; heavy species missing in the first sampling.

General: Na(Ca, Mg)-Cl(SO$_4$, HCO$_3$,) brackish marine (Littorina) groundwater. As sampling has been carried out on two occasions, two samples have been chosen as representative and each allocated Category 2. Taken together there is an adequate time series that otherwise would have been missing. Furthermore, missing data from one sampling occasion can be extrapolated from the other.

KFM03A (639.00–646.12 m; mid. vertical elevation of –631.91 m)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)		x			
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					

Drilling Water: HFM06 (12.00–110.70 m; major flow input from ~ 46 m). Typical Na(Ca, Mg)-Cl(HCO_3, SO_4) brackish mixed groundwater type with a weak marine component (1,108 mg/L Cl; 54.5 mg/L Mg) and a $\delta^{18}O$ signature of around –10.60‰ V-SMOW. Tritium is 5.7 TU indicating a modern recharge influence; this is supported by ^{14}C at 61.1 pmC content.

Charge Balance: OK at –3.17 to –1.42%.

Time Series: Sampled from 2004-02-04 to 2004-02-23 (19 days). By ignoring the first sampled groundwater which is influenced by a significant marine component (199 mg/L Mg), the remainder of the time series shows good stability for the major ions (e.g. 5,380–5,430 mg/L Cl). Drilling water is significant showing a small but consistent decease with sampling time (5.50–4.35%). Major ions complete, apart for the initial sample

Isotopes: Complete; inadequate HCO_3 (~ 25 mg/L) for $\delta^{13}C$ and ^{14}C determinations. Change to more depleted $\delta^{18}O$ (around –11.60‰ V-SMOW) suggesting a cold climate influence; tritium is consistently below detection (< 0.8 TU).

Trace elements: Incomplete. Heavy species are absent from all samples; the remainder (i.e. including the REEs) are available for three samples including the chosen one.

General: Na-Ca-Cl($SO_{4,}$) brackish non-marine groundwater. Allocated Category 2 because of > 1% drilling water and incomplete trace element data.

KFM03A (633.50–650.00 m; mid. vertical elevation of –631.10 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)		x			
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					

Drilling Water: HFM06 (12.00–110.70 m; major flow input from ~ 46 m). Typical Na(Ca, Mg)-Cl(HCO_3, SO_4) brackish mixed groundwater type with a weak marine component (1,108 mg/L Cl; 54.5 mg/L Mg) and a $\delta^{18}O$ signature of around –10.60‰ V-SMOW. Tritium is 5.7 TU indicating a modern recharge influence; this is supported by ^{14}C at 61.1pmC content.

Charge Balance: OK at –0.40 to +0.27%.

Time Series: Later installed Monitoring Section to coincide with the above described section. Sampled on four occasions from 2005-06-23 to 2006-10-24 (at intervals of 4 to 7 months). Good stability for the major ions (e.g. 5,570–5,700 mg/L Cl); drilling water significant from 4.35–5.70% with no time trend indicated. Major ions complete, apart for one sample which lacked Fe(tot)/Fe(II) and Mn.

Isotopes: Complete; inadequate HCO_3 (26.90–33.70 mg/L) for $\delta^{13}C$ and ^{14}C determinations; depleted $\delta^{18}O$ (around –11.40‰ V-SMOW) suggesting a cold climate influence; tritium or initial sample at 1.5 TU but remaining two below detection (< 0.8 TU).

Trace elements: Complete.

General: Na-Ca-Cl($SO_{4,}$) brackish non-marine groundwater. Main difference with the previously described section is a slightly higher content of all major ions and more negative deuterium value. Allocated Category 2 because of > 1% drilling water and incomplete trace element data.

KFM03A (803.20–804.20 m; mid. vertical elevation of –792.11 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					x
Time series (adequate)					
Time series (inadequate)					
Time series (absent)					x
Suitable section length					x
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					x
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					x
Environmental isotopes (incomplete)					

Drilling Water: HFM06 (12.00–110.70 m; major flow input from ~ 46 m). Typical Na(Ca, Mg)-Cl(HCO_3, SO_4) brackish mixed groundwater type with a weak marine component (1,108 mg/L Cl; 54.5 mg/L Mg) and a $\delta^{18}O$ signature of around –10.60‰ V-SMOW. Tritium is 5.7 TU indicating a modern recharge influence; this is supported by ^{14}C at 61.1 pmC content.

Charge Balance: OK at –1.27%.

Time Series: One sample collected in 2004-12-13; no time series (6,530 mg/L Cl) with drilling water at 16.50%. Major ions incomplete; no F, Fe(tot)/Fe(II), S^{2-} or TOC.

Isotopes: Complete; inadequate HCO_3 (26.90–33.70 mg/L) for $\delta^{13}C$ and ^{14}C determinations; depleted $\delta^{18}O$ (around –12.70‰ V-SMOW) suggesting a cold climate influence; tritium at 1.3 TU.

Trace elements: Absent.

General: Ca-Na-Cl brackish non-marine groundwater. Allocated Category 5 because of a lack of time series, incomplete major ions and trace elements and > 10% drilling water.

KFM03A (939.50–946.62 m; mid. vertical elevation of –930.50 m)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)			x		
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)			x		
Time series (absent)					
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					

Drilling Water: HFM06 (12.00–110.70 m; major flow input from ~ 46 m). Typical Na(Ca, Mg)-Cl(HCO_3, SO_4) brackish mixed groundwater type with a weak marine component (1,108 mg/L Cl; 54.5 mg/L Mg) and a $\delta^{18}O$ signature of around –10.60‰ V-SMOW. Tritium is 5.7 TU indicating a modern recharge influence; this is supported by ^{14}C at 61.1 pmC content.

Charge Balance: OK at –1.58 to –0.98%.

Time Series: Sampled from 2004-03-03 to 2004-03-29 (26 days). Instability during sampling (e.g. 7,560–8,560 mg/L Cl) reflected by Na and Ca indicating a progressively more saline composition; K, Mg and SO_4 indicated a decrease. Drilling water decreases from 13.00–9.00% during sampling. Major ions complete; TOC lacking but DOC analysed.

Isotopes: Complete; inadequate HCO_3 (9.90–20.00 mg/L) for $\delta^{13}C$ and ^{14}C determinations; depleted $\delta^{18}O$ (–13.00 to –12.40‰ V-SMOW) suggesting a weak cold climate influence; tritium from below detection (< 0.8 TU) to 1.3 TU; selected sample below detection.

Trace elements: Incomplete; no heavy trace elements and REEs etc sporadic but complete for the chosen sample.

General: Na-Ca-Cl($SO_{4,}$) brackish non-marine groundwater with a weak cold climate component. Instability showing an increasing brackish non-marine groundwater with time; additional pumping/sampling would have been desirable to establish stability. Allocated Category 3 because of instability, inadequate time series, and 5–10% drilling water.

KFM03A (980.00–1,001.19 m; mid. vertical elevation of –977.67 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)			x		
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)			x		
Time series (absent)					
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					

Drilling Water: HFM06 (12.00–110.70 m; main input from ~ 46 m). Typical Na(Ca, Mg)-Cl(HCO_3, SO_4) brackish mixed groundwater type with a weak marine component (1,108 mg/L Cl; 54.5 mg/L Mg) and a $\delta^{18}O$ signature of around –10.60‰ V-SMOW. Tritium is 5.7 TU indicating a modern recharge influence; this is supported by ^{14}C at 61.1 pmC content.

Charge Balance: OK at –2.73 to –0.19%.

Time Series: Sampled from 2003-11-06 to 2003-12-08 (29 days). Instability during sampling (i.e. 10,000–9,690 mg/L Cl) reflected by all major ions indicating a progressively less saline composition. Instability is also indicated by the drilling water which decreases from 2.40–1.35% during the first 14 days of sampling, followed by an increase from 2.05–3.85% for the remaining 15 days sampling. Major ions complete; TOC lacking but DOC analysed.

Isotopes: Complete; inadequate HCO_3 (9.00–6.57 mg/L) for $\delta^{13}C$ and ^{14}C determinations; depleted $\delta^{18}O$ (–14.10 to –13.50‰ V-SMOW) suggesting a cold climate influence; tritium consistently below detection (< 0.8 TU).

Trace elements: Incomplete; no heavy trace elements and REEs etc sporadic but complete for the chosen sample.

General: Na-Ca-Cl($SO_{4,}$) brackish non-marine groundwater with an increased cold climate component. Instability but increase in salinity was expected compared to the previously described sample. Additional pumping/sampling would have been desirable to establish stability and short-circuiting is suspected. Allocated Category 3 because of instability, inadequate time series, and incomplete trace element data.

KFM03A (969.50–994.50 m; mid. vertical elevation of –969.14 m)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)		x			
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					

Drilling Water: HFM06 (12.00–110.70 m; major flow input from ~ 46 m). Typical Na(Ca, Mg)-Cl(HCO_3, SO_4) brackish mixed groundwater type with a weak marine component (1,108 mg/L Cl; 54.5 mg/L Mg) and a $\delta^{18}O$ signature of around –10.60‰ V-SMOW. Tritium is 5.7 TU indicating a modern recharge influence; this is supported by ^{14}C at 61.1 pmC content.

Charge Balance: OK at –0.69 to +0.64%.

Time Series: Later installed Monitoring Section to coincide closely with the above described section. Sampled on four occasions from 2005-06-23 to 2006-10-25 (at intervals of 4 to 7 months). Small consistent decrease for some of the major ions, i.e. Na and Ca and Cl (10,700–10,400 mg/L); drilling water < 1% but increased to 1.55% at the last sampling occasion. Major ions sporadic (sometimes lacking in Fe(tot)/Fe(II), S^{2-}, Mn, and TOC/DOC) but complete for the selected sample.

Isotopes: Complete; inadequate HCO_3 (7.46–10.90 mg/L) for $\delta^{13}C$ and ^{14}C determinations; depleted $\delta^{18}O$ (around –13.80‰ V-SMOW) suggesting a cold climate influence; tritium below detection (< 0.8 TU).

Trace elements: Complete for selected sample.

General: Na-Ca-Cl($SO_{4,}$) brackish non-marine groundwater. Main difference with the previously described section is a slightly higher content of all major ions and more depleted $\delta^{18}O$ (this supports the allocation of Category 3 for that sample). Allocated Category 2 for this present sample is because of instability; last sample was not selected because of an increase in tritium. Possible influence from short-circuiting is suspected.

KFM03A

Tube samples sampled every 50 m from 0.00–945 m (20030630) are considered unrepresentative and allocated Category 5.

KFM04A (230.50–237.64 m; mid. vertical elevation of –197.00 m)

Borehole KFM04A is 1,001.42 m long (vertical depth of 832.63 m), cased to 107.42 m, and inclined at 60.08° from the horizontal. The borehole was angled from just outside the candidate area (i.e. the altered zone; dominated by fracture domain FFM04) towards the NE, entering the candidate area and intersecting fracture domain FFM01 at 500 m borehole length. Some earlier documentation of groundwater quality is given in R-05-17.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)			x		
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)			x		
Time series (absent)					
Suitable section length					
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)					
Environmental isotopes (incomplete)			x		

Differential Flow Log: Borehole KFM04A records significant transmissivity values from 110–240 m (range $10^{-7.8}$–$10^{-4.5}$ m^2/s) and 260–360 m (range 10^{-9}–10^{-6} m^2/s) with an individual peak at around 420 m (to $10^{-7.9}$ m^2/s). The highest values between 200–240 m mark the penetration of the major gently-dipping deformation zone ZFMA2. The moderate transmissivity at 260–360 m partly coincides with the gently-dipping deformation zone ZFMNE1188. 'Undisturbed' flow (without pumping) indicates groundwater movement from the borehole out into the bedrock at 200–210 m and 340–360 m borehole length, and from approximately 110 m, 160–180 m, and 235 m borehole lengths. Pumping indicates flow from the bedrock to the borehole without exception.

The single hole injection test results were generally consistent with the results from the earlier differential flow logging in KFM04A. Some differences were found, however, particularly for sections of low transmissivity.

Electric Conductivity log: This was conducted when the probe was both lowered and raised in the open borehole, and with and without pumping in each case. Without pumping the salinity is around 1.8 S/m (~ 6,000 mg/L Cl) and this concentration is quite uniform along almost the full length of the open borehole; a very small increase at from 950–1,000 m is recorded. Pumping on two occasions four days apart showed a successive but uniform dilution of the borehole water down to 1.4–1.6 S/m.

The borehole is therefore characterised by brackish marine water which may be explained by. a) drilling water from HFM10, or b) that KFM04A is drilled into the same reservoir of brackish marine formation water as pumped via HFM10. Hydrochemical logging was carried out in the borehole prior to the differential flow measurements. This showed a high flushing water content along the borehole from about 30–40% between 200–600 m, to about 50% below 600 m depth. Subsequent CCC chemical sampling from two selected borehole sections is estimated to have removed 6 m^3 of water leaving around an estimated 7–15% of residual drilling water in each of the sections. This shows that inadequate pumping has been carried out during the sampling process.

Drilling Water: HFM10 (11.80–150.00 m; major flow input from 25–48 m). Typical Na(Ca, Mg)-Cl(HCO_3, SO_4) brackish marine groundwater type (4,466 mg/L Cl; 161 mg/L Mg) with a enriched $\delta^{18}O$ signature of around –9.50‰ V-SMOW. Tritium is 1.9 TU indicating a modern recharge component, but generally not recent in age (i.e. ^{14}C at 33 pmC content). During drilling 655 m^3 drilling water was used and the uranine budget suggests that at least 100 m^3 of the flushing water was lost to the borehole and the adjacent host bedrock. Subsequent cleaning/clearing of the borehole removed a further 3,466 m^3 water.

Charge Balance: OK with –3.22 to –0.46%.

Time Series: Sampled from 2004-01-16 to 2004-02-12 (27 days). Instability indicated by an increase in salinity (5,480–5,680 mg/L Cl) reflected also by an irregular, but small increase in Mg (212–246 mg/L). These changes may reflect the gradual decrease in drilling water content during the sampling occasion (11.50–7.65%). Major ions complete.

Isotopes: Incomplete; no $\delta^{13}C$ or ^{14}C. Enriched $\delta^{18}O$ (–9.00 to –9.60‰ V-SMOW); under detection tritium (< 0.8 TU) apart from the initial sample (1.00 TU).

Trace elements: Partial coverage but heavy species absent. All trace elements absent from the selected sample.

General: Na-Ca (Mg)-Cl (SO_4,HCO_3) brackish marine groundwater type (Littorina). Allocated Category 3 because of instability during sampling, a lack of carbon isotope data and > 5% drilling water.

NOTE: A single sample (8287) taken in 2007-04-11 from section 230.00–245.00 m confirmed a typical Littorina-type groundwater with 5,780 mg/L Cl, 165 mg/L Mg, a value of ^{14}C at 19.9 pmC and below detection tritium. Also a complete coverage of major ions and trace elements. Unfortunately no drilling water content was recorded.

References: P-04-47, P-04-109, P-04-190, P-04-293.

KFM04A (354.00–361.13 m; mid. vertical elevation of –357.57 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)			x		
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)					
Time series (absent)			x		
Suitable section length					
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					

Drilling Water: HFM10 (11.80–150.00 m; major flow input from 25–48 m). Typical Na(Ca, Mg)-Cl(HCO_3, SO_4) brackish marine groundwater type (4,466 mg/L Cl; 161 mg/L Mg) with a enriched δ^{18}O signature of around –9.50‰ V-SMOW. Tritium is 1.9 TU indicating a modern recharge component, but generally not recent in age (i.e. 33 pmC content). During drilling 655 m^3 drilling water was used and the uranine budget suggests that at least 100 m^3 of the flushing water was lost to the borehole and the adjacent host bedrock. Subsequent cleaning/clearing of the borehole removed a further 3,466 m^3 water.

Charge Balance: OK with 0.41%.

Time Series: One sample taken in 2004-05-10; 5,780 mg/L Cl and 165 mg/L Mg with a drilling water content of 6.5%. Major ions complete apart from TOC.

Isotopes: Complete. Enriched δ^{18}O (–9.50‰ V-SMOW); ^{14}C at 19.87 pmC and under detection tritium (< 0.8 TU).

Trace elements: Complete.

General: Na-Ca (Mg)-Cl (SO_4,HCO_3) brackish marine groundwater type (Littorina). Allocated Category 3 because of a lack of time series and > 5% drilling water.

KFM04A

Tube samples sampled every 50 m from 0.00–945 m (2003-12-08) are considered unrepresentative and allocated Category 5.

KFM05A (100.00–121.60 m; mid. vertical elevation of –90.41 m)

Borehole KFM05A is 1,002.71 m long (vertical depth of 831.57 m), cased to 110.10 m, inclined at 59.80° from the horizontal, and angled to the east to intersect the major gently-dipping deformation zone, ZFMA2, near the surface, and then fracture domains FFM02 and FFM01 (containing several gently-dipping deformation zones) at increasing depth.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)				x	
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)				x	
Time series (absent)					
Suitable section length					
Sampling during drilling				x	
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)				x	
Major ions (incomplete)					
Environmental isotopes (complete)					
Environmental isotopes (incomplete)				x	

Differential Flow Log: Borehole KFM05A records significant transmissivity values from 110–180 m (range 10^{-9}–$10^{-3.5}$ m^2/s) with individual peaks at around 255 m (to $10^{-7.9}$ m^2/s) and around 700–720 m (to 10^{-8} m^2/s). The highest values between 110–180 m reflect the shallow bedrock aquifer in fracture domain FFM02. 'Undisturbed' flow (without pumping) indicates groundwater movement from the borehole out into the bedrock at approximately 175 m and 265 m borehole length, and into the borehole from the bedrock at depths from 110–165 m. Pumping indicates flow from the bedrock to the borehole without exception.

The injection test results, carried out after the differential flow logging, where generally consistent, despite some discrepancies in calculated transmissivities in the 5 m sections.

Electric Conductivity log: This was conducted when the probe was both lowered and raised in the open borehole, and pumping was used. This showed a uniform salinity (1.45 S/m; ~5,000 mg/L Cl) along the complete length of the open borehole. No comparison could be made with the hydrochemical logging as this was not carried out.

The borehole is therefore characterised by brackish marine water which may be explained by. a) drilling water from HFM13 (see below), or b) that KFM05A is drilled into the same reservoir of brackish marine formation water as that pumped via HFM13. In the absence of hydrochemical logging this issue could not be resolved, but it is almost certainly a mixture of both sources.

Drilling Water: HFM13 (14.90–209.55 m; no recorded major flow input depth). Typical Na(Ca, Mg)-Cl(HCO_3, SO_4) mixed brackish marine groundwater type (~ 2,500 mg/L Cl; 100 mg/L Mg) with a enriched $\delta^{18}O$ signature of around –10.80‰ V-SMOW. Tritium is 1-2 TU indicating a modern recharge component, but most is an old component (i.e. ^{14}C at 30–40 pmC content). The core drilling of the borehole consumed 1,090 m^3 of drilling water and the volume of returned water pumped from the borehole during drilling was 3,500 m^3.

NOTE: Technical problems plagued the hydrochemical characterisation of KFM05A, in particular short-circuiting around the installed packer system during sampling. This resulted in mixed open borehole waters being sampled from the packed-off borehole sections. This was compounded by the limited number of transmissive sections available for sampling at depths of interest. Consequently, only one sample is included in the present F.2.3 database, that of a shallow near-surface groundwater collected during drilling.

Charge Balance: OK with –0.22%.

Time Series: One sample taken in 2004-02-17 with 4,370 mg/L Cl and 197 mg/L Mg; drilling water was 5.25%. Major ions incomplete (no Fe(tot)/Fe(II), S^{2-}, Mn,or DOC).

Isotopes: Complete. Enriched $\delta^{18}O$ (–8.50‰ V-SMOW); tritium at 1.5 TU and ^{14}C at 13.8 pmC suggesting an old groundwater mixed with a modern, near-surface component.

Trace elements: Absent.

General: Na-Ca (Mg)-Cl (SO_4, HCO_3) brackish marine groundwater type (Littorina). Allocated Category 4 because of absence of time series, 5.25% drilling water, and incomplete major ions. Composition is what would be expected at this bedrock level based on site knowledge.

References: P-04-191, P-05-56, P-05-79.

KFM06A (0.00–100.30 m; mid. vertical elevation of –39.37 m)

Borehole KFM06A is 1,000.64 m long (vertical depth of 831.37 m), cased to 100.40 m, and inclined at 60.00° to the horizontal. The borehole was angled to the NW penetrating successively fracture domains FFM02, FFM01 and eventually FFM06 at maximum depth.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)				x	
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)				x	
Time series (absent)					
Suitable section length					
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					

Differential Flow Log: Borehole KFM06A records significant transmissivity values from 100–400 m (range 10^{-9}–$10^{-4.8}$ m^2/s) with an individual peak at around 740–770 m (range $10^{-7.8}$ – $10^{-6.7}$ m^2/s). The high values: a) between 100–190 m include the depth influence of the shallow bedrock aquifer in FFM02, b) between 200–280 m mark the intersection with the steeply-dipping deformation zone ZFM60B, and c) between 320–360 m mark the intersection with the steeply-dipping deformation zone ZFM60A. The peak at 740–770 m corresponds to the intersection with the deformation zone ZFM725. 'Undisturbed' flow (without pumping) indicates groundwater movement along specific pathways from the borehole out into the bedrock at 300–400 m and at 745 m. Pumping indicates flow from the bedrock along all pathways to the borehole without exception.

The single hole injection test results were generally consistent with the results from the earlier differential flow logging in KFM06A. Some differences were found, however, particularly for sections of low transmissivity.

Electric Conductivity log: Without pumping the log shows average values around 1.6 S/m (~ 5,500 mg/L Cl) down to approximately 600 m, after which there is an irregular decrease to around 1.3 S/m (~ 4,500 mg/L Cl) at the hole bottom. This higher salinity to approx. 600 m probably results from groundwaters of greater salinity (i.e. groundwaters originating from the series of highly transmissive sections extending down to around 300 m) entering into and moving down along the borehole. Movement downhole will be largely density driven and the extent will depend on the density of the groundwater mixture already in the borehole. The decrease in salinity from 600 m towards the bottom of the borehole is due to a high content of less saline drilling water (measured at 60–70% during later hydrochemical logging).

As a result of pumping there is a general decrease to around 1.4 S/m (~ 5,000 mg/L Cl) extending down to around 600 m (where the EC indicates similar salinities to the water mixture in the hole bottom prior to pumping), but particularly from 270–360 m (to around 1.25–1.30 S/m; (~ 4,500 mg/L Cl). This latter decrease coincides with the deformation zone which indicated flow from the borehole into the bedrock under static (non-pumping) conditions.

During drilling, therefore, various amounts of drilling water under high pressure have been introduced into the moderate to high transmissive zones extending down to around 360 m, and subsequently partly removed during logging associated with pumping. Hydrochemical logging of the borehole carried out 37 days after completion of drilling, and 7 days after differential flow measurements (see below), showed a gradual increase of 5–70% drilling water from 100–800 m; this was followed by a small decrease to around 66% towards the bottom of the borehole.

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 2006-09-11. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) brackish marine groundwater (~3,910 mg/L Cl; 180 mg/L Mg) with a δ^{18}O signature of –9.9‰ V-SMOW. A value of δ^{13}C at 34.3 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU). Drilling of the 1,000 m long borehole consumed 1,087 m^3 of drilling water and the volume of returned water pumped from the borehole during drilling was 1,968 m^3. Approximately 400 m^3 of the drilling water was lost to the borehole and the adjacent host bedrock.

Charge Balance: OK with 0.49–1.64%.

Time Series: Two samples taken on the same day (2003-12-08); instability (209–295 mg/L Cl; 247–285 mg/L Na). Major ions incomplete (no Fe(tot)/Fe(II), S^{2-}, Mn or DOC).

Isotopes: Complete for second sample. δ^{18}O (–11.30‰ V-SMOW); tritium at 9.30 TU and ^{14}C at 54.51 pmC.

Trace elements: Absent.

General: Na-HCO_3-Cl brackish groundwater of young recharge character. Allocated Category 4 because of instability during sampling, inadequate time series and potential mixing in the long borehole section.

References: P-05-15, P-05-33, P-05-165, P-05-178.

KFM06A (353.50–360.62 m; mid. vertical elevation of –301.99 m)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)			x		
Drilling water (> 10%)					
Time series (adequate)			x		
Time series (inadequate)					
Time series (absent)					
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 20060911. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) groundwater with a Littorina-type signature (~3,910 mg/L Cl; 180 mg/L Mg) with a δ^{18}O signature of –9.9‰ V-SMOW. A value of δ^{13}C at 34.3 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU).

Charge Balance: OK at –0.31 to +1.09%.

Time Series: Sampled from 2005-02-15 to 2005-03-07 (21 days). Initial decrease in salinity during 9 days (4,710–4,600 mg/L Cl) before stabilising (reflected by the other major ions also) at around 4,560 mg/L Cl for the rest of the sampling period; drilling water contents during the sampling period varied from 6.65–8.00% with no distinctive trend recorded. Complete major ions for most samples.

Isotopes: Complete for the final sample; $\delta^{18}O$ (–11.85 to –11.00‰ V-SMOW); a value of ^{14}C at 29.23 pmC indicates on 'old' post-glacial groundwater type and tritium was consistently under detection (< 0.8 TU).

Trace elements: Incomplete, no heavy species.

General: Na-Ca(Mg)-Cl(HCO_3, SO_4) mixed brackish groundwater with a weak marine component (~ 80 mg/L Mg). Allocated Category 3 because > 5% drilling water content.

KFM06A (341.00–362.00 m; mid. vertical elevation of –297.30 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)				?	
Drilling water (≤ 5%)				?	
Drilling water (≤ 10%)				?	
Drilling water (> 10%)				?	
Time series (adequate)				x?	
Time series (inadequate)					
Time series (absent)					
Suitable section length				x	
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)				x	
Major ions (incomplete)					
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 20060911. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) groundwater with a Littorina-type signature (~3,910 mg/L Cl; 180 mg/L Mg) with a $\delta^{18}O$ signature of –9.9‰ V-SMOW. A value of $\delta^{13}C$ at 34.3 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU).

Charge Balance: OK at –0.63 to +0.88%.

Time Series: Later installed Monitoring Section at approximately the same level as the previously described sample. Sampled on two occasions from 2006-06-20 to 2006-10-09 (interval of 3.75 months). Appears stable (4,650–4,620 mg/L Cl) although inadequate time series; no drilling water recorded. Complete major ions for the second sample.

Isotopes: Complete; $\delta^{18}O$ (–11.50‰ V-SMOW) corresponding to within the recharge range; a value of 30.55 pmC indicates on old groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.10 TU).

Trace elements: Complete for the second sample.

General: Na-Ca(Mg)-Cl(HCO_3, SO_4) mixed brackish groundwater with a weak marine component (~ 80 mg/L Mg). Allocated Category 4 mainly because of an absence of recorded drilling water content.

KFM06A (768.00–775.12 m; mid. vertical elevation of –645.34 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)		x			
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 20060911. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) groundwater with a Littorina-type signature (~3,910 mg/L Cl; 180 mg/L Mg) with a $\delta^{18}O$ signature of –9.9‰ V-SMOW. A value of $\delta^{13}C$ at 34.3 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU).

Charge Balance: OK at –1.57 to +1.30%.

Time Series: Sampled from 2004-12-14 to 2005-01-31 (48 days). After the first 15 days general stabilisation was achieved for the rest of the sampling period (6,840–7,150 mg/L Cl). There are, however, indications that with time there is an increasing brackish non-marine component entering the borehole section (21.7–3.9 mg/L Mg), and this correlates with a consistent decrease in drilling water content (10.80–1.55%) which originates from shallower depths and contains a weak marine component. Complete major ions except for TOC.

Isotopes: Complete; inadequate HCO_3 (5.72 mg/L) for $\delta^{13}C$ and ^{14}C determinations; weakly depleted $\delta^{18}O$ (around –12.00 to –11.20‰ V-SMOW); tritium below detection (< 0.8 TU) after the initial 15 days.

Trace elements: Absent.

General: Ca-Na-Cl brackish non-marine groundwater. Allocated Category 2 because of > 1% drilling water, small degree of instability during sampling and an absence of trace element data.

KFM06A (738.00–748.00 m; mid. vertical elevation of –622.03 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)				?	
Drilling water (≤ 5%)				?	
Drilling water (≤ 10%)				?	
Drilling water (> 10%)				?	
Time series (adequate)				x?	
Time series (inadequate)					
Time series (absent)					
Suitable section length				x	
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)				x	
Major ions (incomplete)					
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 20060911. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) groundwater with a Littorina-type signature (~3,910 mg/L Cl; 180 mg/L Mg) with a $\delta^{18}O$ signature of –9.9‰ V-SMOW. A value of $\delta^{13}C$ at 34.3 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU).

Charge Balance: OK at +1.3 to +1.7%.

Time Series: Later installed Monitoring Section at around 23 m deeper than the level of the previously described sample. Sampled on two occasions from 2006-06-21 to 2006-10-09 (interval of 3.75 months) and appears stable (6,220–6,200 mg/L Cl); no drilling water recorded. Complete major ions for the second sample.

Isotopes: Complete; inadequate HCO_3 (24 mg/L) for $\delta^{13}C$ and ^{14}C determinations; $\delta^{18}O$ (–11.70‰ V-SMOW) and tritium is present (1.1–1.7 TU).

Trace elements: Complete for the second sample.

General: Ca-Na-Cl brackish non-marine groundwater which has a composition similar to the initial sample collected from approximately the same depth interval described above. This suggests that during the 1.5 to 2 year interval between both sampling occasions (2004 and 2006) the initial borehole section has become contaminated and inadequate pumping in the monitoring section has failed on both occasions to access the representative formation water recorded in 2004. Allocated Category 4 because of inadequate time series (i.e. pumping) and no recorded drilling water content.

KFM06A

Tube samples sampled every 50 m from 0.00–970 m (20041028) are considered unrepresentative and allocated Category 5.

KFM06C (531.20–546.27 m and 531.00–540.00 m; mid. vertical elevation of –435.71 m and –434.84 m respectively)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)				x	x
Time series (adequate)					
Time series (inadequate)					
Time series (absent)				x	x
Suitable section length				x	x
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	x
Major ions (complete)				x	
Major ions (incomplete)					x
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					x

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 20060911. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) groundwater with a Littorina-type signature (~3,910 mg/L Cl; 180 mg/L Mg) with a $\delta^{18}O$ signature of –9.9‰ V-SMOW. A value of $\delta^{13}C$ at 34.3 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU).

Charge Balance: OK at –3.72 to +0.64%.

Time Series: Both samples are taken from approximately the same depth interval; the first sample was taken in 2005-05-19 and the later installed Monitoring Section in 2006-10-10, almost 1.5 years later. Both have considerable drilling water contents (20% and 27.3% respectively) and the second sample is characterised by lower concentrations of all the major ions apart from Ca. Incomplete major ion coverage for the first sample (no Fe(tot)/Fe(II), F, S^{2-}, Mn or DOC). Complete major ions for the second sample.

Isotopes: Absent for the first sample. Complete for the second sample; $\delta^{18}O$ (–10.90‰ V-SMOW), old groundwater indicated by ^{14}C at 30.1 pmC, and small amounts of tritium are present (0.9 TU) of unknown origin.

Trace elements: Absent for the first sample. Complete for the second sample.

General: Both groundwaters are Na-Ca(Mg)-Cl mixed brackish marine in type, significantly influenced by the high drilling water composition of brackish marine type. The first sample is allocated Category 5 because of an absence of time series, high drilling water content, incomplete major and trace element data and an absence of isotope data. The second sample is allocated Category 4 because of complete major and trace element data and complete isotope data. This sample may therefore be of some use when the conservative parameters (namely Cl and ^{18}O) are corrected for drilling water dilution.

KFM06C (647.00–666.00 m; mid. vertical elevation of –527.04 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					x
Time series (adequate)					
Time series (inadequate)					
Time series (absent)					x
Suitable section length					x
Sampling during drilling					x
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x

Drilling Water: HFM05 (0–200.10 m; no recorded major flow input depth); sampled in 20060911. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) groundwater with a Littorina-type signature (~3,910 mg/L Cl; 180 mg/L Mg) with a $\delta^{18}O$ signature of –9.9‰ V-SMOW. A value of $\delta^{13}C$ at 34.3 pmC indicates on 'old' post-glacial groundwater type with a younger, near-surface mixing component suggested by the presence of tritium (1.3 TU).

Charge Balance: OK at –0.27%.

Time Series: One sample taken from an installed Monitoring Section in 20061010, i.e. no time series. Drilling water is high at 33.60% and overall composition is a diluted version of monitoring section 531.00–540.00 m described above. Incomplete major ions sample (no Fe(tot)/Fe(II), Br, S^{2-}, Mn or TOC/DOC).

Isotopes: Absent.

Trace elements: Absent.

General: Na-Ca(Mg)-Cl mixed brackish marine in type, significantly influenced by the high drilling water composition of brackish marine type. Allocated Category 5 because of an absence of time series, high drilling water content, incomplete major ion data, and an absence of trace element and isotope data.

KFM07A (100.00–305.84 m; mid. vertical elevation of –171.06 m)

Borehole KFM07A is 1,001.55 m long (vertical depth of 761.88 m), cased to 100.40 m and inclined at 60.00° to the horizontal. The borehole was angled to the NW, close to the altered zone at the margin of the candidate area, penetrating successively fracture domains FFM02, FFM01 and eventually FFM05 at maximum depth.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					x
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)					
Time series (absent)					x
Suitable section length					
Sampling during drilling					x
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					x
Environmental isotopes (incomplete)					

Differential Flow Log: Borehole KFM07A records significant transmissivity values from 100–180 m (range $10^{-8.4}$–$10^{-4.5}$ m^2/s) with an individual peak at around 260 m ($10^{-6.9}$ m^2/s). The high values mark the depth influence of the shallow bedrock aquifer in FFM02 and the upper part of FFM01, characterised by gently-dipping deformation zones ZFM1203 and ZFM0404; the isolated peak is not obviously associated to any particular fracture zone. 'Undisturbed' flow (without pumping) indicates groundwater movement along specific pathways from the borehole out into the bedrock at 130–150 m, at 260 m, at 915 m and at 970 m. Pumping indicates flow from the bedrock along all pathways to the borehole without exception, particularly in the 120–150 m interval.

The single hole injection test results were generally consistent with the results from the earlier differential flow logging in KFM07A.

Electric Conductivity log: Without pumping the log shows average values around 1.5 S/m (~ 5,500 mg/L Cl) down to around 300 m, after which there is sharp increase to around 3.6 S/m (~ 4,500 mg/L Cl) at 400 m; this continued uniformly with only a slight increase in salinity to the bottom of the borehole. With pumping there was a marked increase in salinity to about 3.6 S/m from approximately 170–400 m; little change with the 'undisturbed' conditions was recorded along the rest of the borehole.

During drilling, therefore, various amounts of drilling water under high pressure have been introduced into the moderate to high transmissive zones extending down to around 360 m, and subsequently partly removed during logging associated with pumping. Hydrochemical logging of the borehole carried out some 3 months after completion of drilling, and 40 days after differential flow measurements, showed a gradual decrease from 40% to < 5% drilling water from 100–500 m. Thereafter, the drilling water percentage continued uniformly at < 5% to the bottom of the borehole. This variation mirrors closely that of the earlier measured Differential Flow salinity values obtained prior to pumping.

Drilling Water: HFM21 (12.03–200.00 m; no recorded major flow input depth); sampled from 2004-08-10 to 2004-12-13. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) brackish marine groundwater (~3,000 mg/L Cl; 140 mg/L Mg) with an enriched ^{18}O signature of –9.50‰ V-SMOW. An old groundwater is suggested by around 36 pmC and a younger, near-surface mixing component, is indicated by tritium (~ 3 TU). The mixing/homogenisation of different groundwater sources is facilitated by the long borehole section.

Drilling of the 1,000 m long borehole consumed 1,121 m^3 of drilling water and the volume of returned water pumped from the borehole during drilling was 2,300 m^3. Approximately 400 m^3 of the drilling water was lost to the borehole and the adjacent host bedrock.

Charge Balance: OK with +2.02%.

Time Series: One sample taken on 2004-10-28; no time series. Drilling water was 9% and salinity 3,350 mg/L Cl; marine signature indicated by 140 mg/L Mg. Major ions incomplete (no Fe(tot)/Fe(II), S^{2-}, Mn or TOC/DOC).

Isotopes: Complete. δ^{18}O (–9.30‰ V-SMOW); tritium at 1.8 TU and ^{14}C at 22.1 pmC.

Trace elements: Absent.

General: Na-Ca-Mg-Cl($SO_{4,}$ HCO_3) relatively old brackish marine groundwater with a suggested young recharge component. Allocated Category 5 because of a lack of time series, incomplete major ions, and a very long borehole section facilitating mixing from several sources.

References: P-05-63, P-05-133, P-05-170, P-05-187.

KFM07A (848.00–1,001.55 m; mid. vertical elevation of –757.72 m)

Cored Boreholes	Category				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)			x		
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)			x		
Time series (inadequate)					
Time series (absent)					
Suitable section length					
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)					
Major ions (incomplete)			x		
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					

Drilling Water: HFM21 (12.03–200.00 m; no recorded major flow input depth); sampled from 20040810–20041213. Typical mixed Na-Ca-Mg-Cl(HCO_3, SO_4) brackish marine groundwater (~3,000 mg/L Cl; 140 mg/L Mg) with an enriched ^{18}O signature of –9.50‰ V-SMOW. An old groundwater is suggested by around 36 pmC and a younger, near-surface mixing component, is indicated by tritium (~ 3 TU). The mixing/homogenisation of different groundwater sources is facilitated by the long borehole section.

Charge Balance: OK at –0.49 to +1.63%.

Time Series: Sampled from 2005-03-22 to 2005-05-25 (64 days). Salinity somewhat irregular but no marked regular trends (14,100–14,800 mg/L Cl), reflected also by the other major ions. Drilling water is consistently < 1% throughout the sampling period. Incomplete major ions; no Br or TOC.

Isotopes: Complete; inadequate HCO_3 (7.36 mg/L) for $\delta^{13}C$ and ^{14}C determinations; depleted $\delta^{18}O$ (–12.90‰ V-SMOW) and tritium is under detection (< 0.8 TU).

Trace elements: Incomplete for selected sample (no heavy species); otherwise complete for the final sample taken in the series and the data can be extrapolated.

General: Ca-Na-Cl brackish non-marine groundwater with a depleted $\delta^{18}O$ signature, i.e. typical for such depths in the footwall area. Allocated Category 3 because of the long section sampled (hence mixing from different sources) and that it intersects a deep fracture zone at around 970 m depth which has been heavily pumped resulting in possible upconing.

KFM07A

Tube samples sampled every 50 m (some 100 m) from 0.00–850 m (2005-03-09) are considered unrepresentative and allocated Category 5.

KFM08A (100.00–203.51m; vertical elevation: –127.33 m.a.s.l.)

Borehole KFM08A is 1,001.19 m long (vertical depth of 750.89 m), cased to 100.55 m and inclined at ~ 60° from the horizontal. This inclination decreases strongly along the borehole so that it is only ~ 36° on completion of drilling. The purpose was to collect representative groundwater samples from a limited rock volume and from individual water-bearing fractures or fracture zones in the target volume at repository depths. With increasing depth, the cored borehole intersects mainly fracture domain FFM01 apart from FFM05 at around 840–920 m.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)				x	
Time series (adequate)					
Time series (inadequate)					
Time series (absent)				x	
Suitable section length					
Sampling during drilling				x	
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)				x	
Environmental isotopes (incomplete)					

Differential Flow Log and Injection Tests: Three borehole length horizons of enhanced transmissivity occur: one intermediate at 100–180 m (~10^{-8} m^2/s), one major horizon at 180–280 m (~$10^{-5.8}$ m^2/s), a further intermediate horizon at 400–500 m (~$10^{-7.3}$ m^2/s), in addition to a single fracture at 690 m (~$10^{-5.9}$ m^2/s). The upper horizon incorporates the shallow bedrock aquifer, the 180–280 m horizon includes the ZFM1061A deformation zone (200–262 m), whilst the others include possible deformation zones. Injection test data show that sections 184–199 m, 274–279 m and 684–689 m contribute most to the total transmissivity in KFM08A.

Without pumping, i.e. open hole conditions, the groundwater flow is from the borehole to the surrounding bedrock in the upper 500 m, and the converse for the deeper single fracture at 690 m borehole length. With pumping, all flow is from the bedrock to the borehole.

Electric Conductivity log: The recorded salinity along the borehole with and without pumping show little difference (~ 0.1 S/m); lower EC characterises the upper 190 m borehole length (0.7–0.8 S/m), increased EC from the transmissive horizon at 190–290 m (up to ~ 1.3 S/m) and higher EC (1.3–1.4 S/m) from the lower 290–929 m. These data imply that there is little effect of drilling water on the formation groundwater salinity from borehole activities and that the EC profile reflects the variation in the formation groundwater salinity. However, the drilling water salinity at ~ 2,800 mg/L Cl (i.e. ~ 0.9 S/m) could quite easily be masked by the formation groundwater salinity, shown by the EC log below 300 m to be at least ~ 4,400 mg/L Cl. Hydrochemical logging of the open borehole carried out 10 days after the differential flow measurements show a steady increase in drilling water from just over 15% at 100 m to a maximum of 40–45% at 450 m; this high percentage of drilling water continues to the bottom of the borehole. This underlines the importance of combining all available data to resolve the effects from borehole activities both prior to locating suitable sections for sampling, and subsequently when assessing groundwater quality.

Drilling Water: HLX22 (12.00–221.00 m; major flow input at ~ 45 m): Na-Ca(Mg)-Cl (HCO_3-SO_4) brackish marine groundwater (~2,800 mg/L Cl; 108 mg/L Mg) with an enriched $\delta^{18}O$ signature (–9.40‰ V-SMOW). Tritium data reflect a small young component (1.9 TU); overall old groundwater indicated by ^{14}C at 22.9 pmC. Volume of drilling water used was 1,196 m^3 with 1,210 m^3 returned, indicating a hydraulically tight borehole length with little loss to the surrounding bedrock. Prior to sampling nitrogen flushing was carried out five times from the hole bottom removing a further 29 m^3 borehole water. Subsequent pumping and monitoring from packed-off borehole section 683.5–690.6 m showed the percentage drilling water decreasing from over 40% to a levelling off at 5% during actual sampling.

Charge Balance: OK ranging from –2.76%.

Time Series: Inadequate, with only one sample taken in 2005-05-02; brackish (1,950 mg/L Cl) with a possible weak marine component (25.8 mg/L Mg); drilling water is present in large amounts (17.10%). Incomplete major ions (no Fe(tot)/Fe(II), S^{2-} or TOC/DOC).

Isotopes: Complete; inadequate HCO_3 (23.8 mg/L) for $\delta^{13}C$ and ^{14}C determinations; much depleted $\delta^{18}O$ (–14.50‰ V-SMOW), and tritium is 0.90 TU suggesting a modern component or, more likely, contamination.

Trace elements: Absent.

General: Na-Ca-Cl brackish glacial type groundwater. Allocated Category 4 because of an absence of time series, incomplete major ions, high drilling water content and a long sampled borehole section which facilitates mixing of different groundwater sources. This sample may be of some use when the conservative parameters (namely Cl and ^{18}O) are corrected for drilling water dilution.

References: P-05-43, P-05-206, P-06-194, P-06-63.

KFM08A (683.50–690.64 m; vertical elevation –546.42 m.a.s.l)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)		x			
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					

Drilling Water: HLX22 (12.00–221.00 m; major flow input at ~ 45 m): Na-Ca(Mg)-Cl (HCO_3-SO_4) brackish marine groundwater (~2,800 mg/L Cl; 108 mg/L Mg) with an enriched $\delta^{18}O$ signature (–9.40‰ V-SMOW). Tritium data reflect a small young component (1.9 TU); overall old groundwater indicated by ^{14}C at 22.9 pmC.

Charge Balance: OK at –0.73 to +0.35%.

Time Series: Sampled from 2005-09-13 to 2005-10-31 (48 days). Good stability (6,010–6,190 mg/L Cl; 1,470–1,560 mg/L Na); drilling water constant at 4.25–5.40% during sampling. Complete major ions (only TOC lacking).

Isotopes: Complete; inadequate HCO_3 (9.47–13.00 mg/L) for $\delta^{13}C$ and ^{14}C determinations; depleted $\delta^{18}O$ (–13.60 to –13.20‰ V-SMOW) and tritium is consistently under detection (< 0.8 TU) apart from the first sample in the series at 2.6 TU.

Trace elements: Complete.

General: Ca-Na-Cl brackish non-marine groundwater with a depleted $\delta^{18}O$ signature, i.e. typical for such depths in the footwall area. Allocated Category 2 because > 1% drilling water.

KFM08A

Tube samples sampled every 50 m (some 100 m) from 10.00–835 m (2005-05-30) are considered unrepresentative and allocated Category 5.

KFM08C (683.40–684.40 m; mid. vertical elevation of –569.15 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					x
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)					x
Time series (absent)					
Suitable section length					x
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					x
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)					x

Drilling Water: HLX22 (12.00–221.00 m; major flow input at ~ 45 m): Na-Ca(Mg)-Cl (HCO_3-SO_4) brackish marine groundwater (~2,800 mg/L Cl; 108 mg/L Mg) with an enriched $\delta^{18}O$ signature (–9.40‰ V-SMOW). Tritium data reflect a small young component (1.9 TU); overall old groundwater indicated by 22.9 pmC.

Charge Balance: OK at +1.43%.

Time Series: Sampled on 2006-09-15 to 2006-09-26 (11 days). Instability indicated during the sampling period (5,840–6,640 mg/L Cl); drilling water decreased from 10.90–8.5% during the same period. Incomplete major ion coverage for the first sample (only Cl); second sample also incomplete (no Fe(tot)/Fe(II), S^{2-} or TOC/DOC).

Isotopes: Absent.

Trace elements: Absent.

General: Ca-Na-Cl brackish non-marine in type, influenced by drilling water of brackish marine type. Both samples allocated Category 5 because of inadequate time series, high drilling water content, incomplete major ions, absence of trace element data and an absence of isotope data.

KFM08D (669.70–676.84 m; vertical elevation: –540.63 m)

Borehole KFM08D is 942.3 m long (vertical depth of 750.89 m), cased to 60.8 m and inclined at ~ 55.19° from the horizontal towards the ESE. The purpose was to further characterise the groundwater chemistry in the candidate area to repository depths.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)		x			
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					

Differential Flow Log and Injection Tests: The total number of flowing fractures was 35; the highest fracture transmissivity (1.39×10^{-5} m^2/s) was detected at 82.1 m borehole length and other high transmissive fractures at 149.8 m, 148.0 m and 82.4 m borehole lengths. No flowing fractures were identified below 832.2 m borehole length. Three horizons of enhanced transmissivity occur: one major horizon at 80–160 m ($10^{-4.9}$ m^2/s), and two weaker horizons at 380–400 m (10^{-7} m^2/s) and 665–740 m ($10^{-6.8}$ m^2/s), in addition to a single fracture at 830 m ($10^{-7.8}$ m^2/s). Flow directions under open hole conditions are dominantly from the borehole to the surrounding bedrock in the upper horizon, and the converse for the deeper two horizons. With pumping all flow is into the borehole.

No injection test data are presently available.

Electric Conductivity log: Some problems were encountered during this measurement in that there was an inconsistency between the upward and downward measurements believed to be due to fine solid material in the open borehole below 500–600 m. Comparing, therefore, only the downward logging data in the upper 500 m without pumping, i.e. under natural flow conditions, there is a low brackish groundwater (~0.7–1.1 S/m) within the high transmissive horizon from 80–160 m borehole length, followed by only a very small increase (~ 1.05–1.2 S/m) down to 840 m borehole length where an additional small increase (to ~ 1.3 S/m) continues to 920 m borehole length. Following pumping, an overall small increase in salinity (up to ~ 0.1 S/m) was observed along the borehole length. Initially this implies that the water removed from the bedrock during pumping has not been affected significantly by borehole activities. However, as shown below, the drilling water salinity at ~ 2,800 mg/L Cl (i.e. ~ 0.9 S/m) could quite easily be masked by the formation groundwater salinity shown by the log to be at least ~ 5,000 mg/L Cl.

Drilling Water: HFM22 (12.00–221.00 m; major flow input at ~ 45 m): (Na-Ca-Mg)-(Cl-HCO_3-SO_4) Littorina-type groundwater (~2,800 mg/L Cl; 108 mg/L Mg) with an enriched $\delta^{18}O$ signature (–9.40‰ V-SMOW). Tritium data reflect a small young component (1.9 TU); overall old water indicated by ^{14}C at 22.9 pmC. Volume of drilling water used was 884 m^3 and the returned water volume was 1,976 m^3; of this 380 m^3 of drilling water were believed to have been lost to the borehole. Borehole cleaning using nitrogen gas flushing removed a further 14 m^3 water.

Charge Balance: OK ranging from –0.24 to +2.02%.

Time Series: 2007-05-14 to 2007-06-18 (35 days); reasonable time series. Instability for the first 25 days of pumping (6,620–7,340 mg/L Cl) followed by stability for the remaining sampling period although an extended sampling time would have been desireable. Drilling water decreased systematically from 20.10 to 5.40% during the sampling period. Complete major ions (only TOC lacking).

Isotopes: Complete. No ^{13}C or ^{14}C data due to low bicarbonate content (< 10 mg/L); tritium data show a small range from under detection to 1.80 TU suggesting some young water component. $\delta^{18}O$ values are somewhat depleted at –12.30 to –11.90‰ V-SMOW indicating a possible weak cold climate component.

Trace elements: Good coverage.

General: Ca-Na-Cl(SO_4) brackish non-marine groundwater. Allocated Category 2 mainly because of the ≤ 5% drilling water content.

References: SKB P-07-84, SKB P-07-190.

KFM08D (828.40–835.54 m; vertical elevation –664.06 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)			x		
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)			x		
Time series (absent)					
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					

Charge Balance: OK ranging from –0.71 to +1.12%.

Time Series: 2007-04-04 to 2007-04-30 (26 days); inadequate time series. Sampling period showed an increase in salinity from 7,590–8,160 mg/L Cl which was accompanied by a small increase in Ca and Br and decrease in Mg. Drilling water decreased systematically from 15.40 to 4.25%.

Isotopes: Complete. No ^{13}C and ^{14}C data – too low bicarbonate content (< 10 mg/L); tritium data show a small range of 1.00–1.80 TU suggesting some young water component – although irregular there is the suggestion of a small increase during the sampling period. Bearing in mind that the drilling water content is similar to level 669-70-676.84 m which recorded low to below detection tritium, this small increase in tritium may suggest some contamination. δ^{18}O values range from –11.90 to –11.60‰ V-SMOW and are slightly more enriched than the preceding level described.

Trace elements: Good coverage.

General: Ca-Na-Cl(SO$_4$) groundwater showing a small but consistent instability of major ion chemistry during the sampling period. Brackish, non-marine groundwater type indicated; no suggestion of significant contamination from the Littorina-type drilling water following the initial 3 weeks of pumping which may reflect the decrease in drilling water during this time. Some doubts about the small compositional irregularities of the major ions, and slightly more enriched δ^{18}O values and higher tritium than expected at this depth which may suggest some weak contamination that additional pumping might have quickly resolved. Some short-circuiting cannot be ruled out bearing in mind the similarity in groundwater chemistry between the two sampled levels, even though there is a vertical depth difference of about 125 m. Allocated Category 3 to accommodate these uncertainties.

KFM09A (100.00–515.51m; vertical elevation: –254.10 m.a.s.l.)

Borehole KFM09A is 799.67 m long (vertical depth of 625.50 m), cased to 7.79 m and inclined at –59.46° from the horizontal towards the SSW outside the candidate area in the 'altered zone'. With increasing depth, the cored borehole intersects fracture domains FFM02, FFM01, FFM05 and FFM04. This borehole was not intended to be prioritised for hydrogeochemistry and therefore it might have been subject to additional contamination from the various borehole activities.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					?
Drilling water (≤ 5%)					?
Drilling water (≤ 10%)					?
Drilling water (> 10%)					?
Time series (adequate)					
Time series (inadequate)					
Time series (absent)					x
Suitable section length					
Sampling during drilling					x
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)					x
Major ions (complete)					
Major ions (incomplete)					x
Environmental isotopes (complete)					x
Environmental isotopes (incomplete)					

Differential Flow Log and Injection Tests: No differential flow log measurements have been reported. However, injection test data show that sections 166.0–171.0 m and 431.0–436.0 m contribute to about half of the transmissivity of the entire borehole.

Electric Conductivity log: No measurements have been reported. Open hole hydrochemical logging (i.e. tube sampling) was carried out just over 4 months after completion of drilling and borehole flushing. This showed an increase in drilling water from < 5% to a maximum of 53% at around 300 m depth. Thereafter, there was a steady decease to around 5% at the bottom of the borehole. The salinity along the borehole increased steadily from fresh water (< 200 mg/L Cl) near the surface to just over 14,000 mg/L at the bottom of the borehole. Maximum salinity occurred at approximately 620 vertical depth.

Drilling Water: Tap water was used to drill borehole KFM09A; this consists of a dilute (6.4 mg/L Cl) Na-Ca – HCO$_3$-SO$_4$ water with 11.3 TU, a δ^{18}O value of –7.2‰ V-SMOW and ^{14}C at 106.36 pmC. Some 861 m^3 were used during drilling with 1,036 m^3 returned.

Charge Balance: OK at +0.76%.

Time Series: Absent, with only one sample taken in 2005-10-06. No drilling water recorded. Incomplete major ions (no Fe(tot)/Fe(II), S^{2-} or TOC/DOC).

Isotopes: Complete. Strongly enriched δ^{18}O (–7.20‰ V-SMOW); tritium is high at 11.3 TU and high ^{14}C at 106.36 pmC.

Trace elements: Absent.

General: Na-Ca-HCO$_3$ fresh water which, together with its isotopic signature, is very close in composition to the tap water used as drilling water. Allocated Category 5 because of an absence of time series, incomplete major ions, no recorded drilling water content (but can be as high as 50% as shown by the hydrochemical logging), and an extremely long borehole sample section which facilitates mixing of different groundwater sources.

References: P-06-52, P-06-95, P-06-217.

KFM09A (785.10–792.24 m; vertical elevation –614.21 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)		x			
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					

Charge Balance: OK ranging from +2.12 to +4.6%.

Time Series: 2006-04-20 to 2006-05-02 (12 days). Sampling period showed a stable chemistry (14,200–14,800 mg/L Cl) reflected by the other major ions. Drilling water ranged from 2.33–1.56%, decreasing systematically with time. Incomplete major ions (no recorded TOC/DOC).

Isotopes: Complete. No $\delta^{13}C$ and ^{14}C data – too low bicarbonate content (< 10 mg/L) for determinations; tritium is under detection (< 0.8 TU) and $\delta^{18}O$ is depleted at –13.12‰ V-SMOW.

Trace elements: Good coverage.

General: Ca-Na-Cl(SO_4) brackish non-marine groundwater with a cold climate input. Allocated Category 2 because of > 1% drilling water.

KFM09A

Tube samples sampled every 50 m from 45.00–795 m (2006-03-07) are considered unrepresentative and allocated Category 5.

KFM09B

Tube samples sampled every 50 m from 60.00–610 m (2006-05-30) are considered unrepresentative and allocated Category 5.

KFM10A (298.00–305.14 m; vertical elevation: –214.77 m)

Borehole KFM10A is 500 m long (vertical depth of 342.58 m), cased to 60.7 m and inclined at ~ 50° from the horizontal towards the NE; it penetrates the hanging wall (i.e. fracture domain FFM03) intersecting the series of gently-dipping deformation zones that characterise the bedrock in this area.. The borehole is located at the SW limit of the target area and hydrochemical investigations were carried out for two reasons: 1) to verify the hypothesis that the groundwater conditions are different within and above the major deformation zone ZFMA2, compared to below the zone, and 2) in order to obtain hydrochemical data from an additional location/borehole section representing the deformation zone ZFMA2.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)		x			
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)		x			
Time series (inadequate)					
Time series (absent)					
Suitable section length		x			
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)		x			
Major ions (complete)		x			
Major ions (incomplete)					
Environmental isotopes (complete)		x			
Environmental isotopes (incomplete)					

Differential Flow Log and Injection Tests: Three zones of enhanced transmissivity occur: one strong at 60–110 m ($10^{-4.9}$ m^2/s), an intermediate one at 300–340 m ($10^{-6.9}$ m^2/s) and single-type fractures at 430–440 m ($10^{-4.8}$ m^2/s) and 480–490 m (10^{-6} m^2/s). These are in general agreement with single hole injection tests carried out at 100, 20, 10 m and 5 m intervals. Uppermost horizon corresponds to the gently-dipping deformation zone ZFM0123, and the 430–440 m and 489–490 m horizons correspond to the gently-dipping major deformation zone ZFMA2. Natural flow (i.e. no pumping) is dominantly from the bedrock to the borehole with some minor flow from the borehole to the bedrock between 300–325 m, 430–440 m and 480–490 m. With pumping all flow is from the bedrock into the borehole.

Electric Conductivity log: Without pumping, i.e. under natural flow conditions, there is one saline irregularity at around 90–100 m and a more distinct salinity break at around 440 m depth; salinity ranges from 0.2–0.4 S/m down along the borehole. Pumping reveals a sharp saline break at the 90–100 m depth (0.2–0.85 S/m) but no significant change in the extent of the salinity change at the 420 m depth although along the borehole in general there is an increase in salinity to 0.5–1.13 S/m. These breaks reflect the major high transmissive zone at 90–100 m and a single fracture at 440 m.

Drilling Water: HLX24 (18.30–151.35 m; major flow input at ~33 m): Na-Ca-HCO_3(Cl, SO_4) mixed brackish groundwater (~500 mg/L Cl; 23.4 mg/L Mg) with a recharge $\delta^{18}O$ signature (–10–90‰ V-SMOW). Tritium data reflect a modern component (7.5 TU). Volume of flushing water used was 479 m^3 and 926 m^3 returned, indicating inflow of formation groundwater into the borehole during drilling. A further 20 m^3 of borehole water were flushed out using pressurised nitrogen gas from the bottom of the borehole.

Charge Balance: OK ranging from –1.62 to –0.68%.

Time Series: 2006-11-03 to 2006-11-26 (23 days). Adequate time series showing a rapid stabilisation after the first sampling to around 4,000 mg/L Cl; this stabilisation applies to all major ions although there is weak indication of increased salinity during the sampling period. This may reflect the gradual decease of drilling water sampled, i.e. a systematic decrease from 12.90–4.45%, and might still be decreasing when sampling was terminated. Complete major ions.

Isotopes: Complete. No $\delta^{13}C$ and ^{14}C data – too low bicarbonate content (20.50 mg/L); tritium data are low ranging from below detection to 1.6 TU (indication of a decease during the sampling period); $\delta^{18}O$ values range from –14.00 to –13.50‰ V-SMOW reflecting a significant cold climate component.

Trace elements: Good coverage.

General: Na-Ca-Cl (SO_4) brackish groundwater with a weak marine component which decreased during the sampling period. Allocated Category 2 because drilling water >1% and also small systematic changes with time towards possibly a more representative sample. Final sample selected as being most representative.

References: SKB P-06-190; SKB P-07-42.

KFM10A (430.00–440.00 m and 436.90–437.90 m; vertical elevations –299.83 m and –301.28 m)

Two single sampling occasions from different sections at approximately the same depth; a period of around 5.5 months separated the samplings.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)			x		
Drilling water (≤ 10%)			x		x
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)			x		
Time series (absent)					x
Suitable section length			x		x
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		x
Major ions (complete)			x		
Major ions (incomplete)			x		x
Environmental isotopes (complete)					
Environmental isotopes (incomplete)			x		x

Drilling Water: HLX24 (18.30–151.35 m; major flow input at ~33 m): Na-Ca-HCO_3(Cl, SO_4) mixed brackish groundwater (~500 mg/L Cl; 23.4 mg/L Mg) with a recharge $\delta^{18}O$ signature (–10–90‰ V-SMOW). Tritium data reflect a modern component (7.5 TU). Volume of flushing water used was 479 m^3 and 926 m^3 returned, indicating inflow of formation groundwater into the borehole during drilling. A further 20 m^3 of borehole water were flushed out using pressurised nitrogen gas from the bottom of the borehole.

Charge Balance: OK ranging from –2.90 to –2.46%.

Time Series: Sampled on one occasion in 2006-11-29 and 2007-04-17; inadequate time series. Compared with the 2006 sampling, the 2007 sampling showed a marked increase in salinity from 3,300–4,900 mg/L Cl which was accompanied by an increase in Na, Ca, Mg and SO_4 and a decrease in HCO_3. Drilling water increased from 3.75–7.22%. Good coverage of major ions for the second sampling in 2007.

Isotopes: No $\delta^{13}C$ and ^{14}C data for the first sampling in 2006; tritium data are significant at 2.9 TU for the first sampling and 2.8 TU for the second; $\delta^{18}O$ values were respectively enriched at –10.10 and –8.60‰ V-SMOW, reflecting a significant marine (Littorina) component coming in during the 2007 sampling. A value of ^{14}C at 29.64 pmC was recorded from the second sampling indicating an old groundwater.

Trace elements: Good coverage for the 2007 sampling; absent for the 2006 sampling.

General: Na-Ca-Mg-Cl(SO_4-HCO_3) groundwater of brackish marine type which became more apparent during the second sampling period in 2007. The tritium contents may be explained partly by the drilling water content, but then an increase in tritium would have been expected in 2007 when there was also an increase in drilling water. Therefore the possibility of anthropogenic contamination from SFR or other sources cannot be excluded.

Thus, in general, large discrepancies in major ion chemistry; no time series and the tritium problem all contribute to quality uncertainty. However, the 2007 sampling of the 430.00–440.00 m borehole length could be acceptable based on what would be expected at this depth and the assessment of the slightly deeper level presented below (478.00–487.49 m). Based on this reasoning a Category 3 has been allocated. The 2006 sampling has been allocated a Category 5 because of insufficient major ion data, no trace element data, no time series and the measured parameters indicate it is not representative for the level sampled.

References: SKB P-06-190; SKB P-07-42.

KFM10A (478.00–487.49 m; vertical elevation of –328.08 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)			x		
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)			x		
Time series (inadequate)					
Time series (absent)					
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)			x		
Environmental isotopes (incomplete)					

Drilling Water: HLX24 (18.30–151.35 m; major flow input at ~33 m): Na-Ca-HCO_3(Cl, SO_4) mixed brackish groundwater (~500 mg/L Cl; 23.4 mg/L Mg) with a recharge $\delta^{18}O$ signature (–10–90‰ V-SMOW). Tritium data reflect a modern component (7.5 TU). Volume of flushing water used was 479 m^3 and 926 m^3 returned, indicating inflow of formation groundwater into the borehole during drilling. A further 20 m^3 of borehole water were flushed out using pressurised nitrogen gas from the bottom of the borehole.

Charge Balance: OK ranging from –1.84 to –0.24%.

Time Series: Sampled from 2006-10-12 to 2006-10-30 (18 days). Adequate time series showing reasonable stability ranging from 4,340–4,720 mg/L Cl; however the final sample decreased to 3,690 mg/L Cl. Stability was also indicated by Na, Ca, Mg, SO_4 and HCO_3 and the salinity decrease in the last sample was accompanied by a decrease in these ions with the exception of HCO_3 which increased. TOC, DOC and Fe were anomalously high in the last sample. Drilling water was low (< 1.25%) until the final sample where it increased to 3.55%. Apart from the first sample, the major ion coverage is good apart from the absence of some TOC data.

Isotopes: Incomplete. $\delta^{13}C$ and ^{14}C data available only for the final sample collected (^{14}C at 33 pmC); tritium data are significant ranging from 1.8–2.1 TU for the first 11 days before increasing to 3.0–3.5 TU during the last 7 days of the sampling campaign. This coincides with the increase in the drilling water. $\delta^{18}O$ values are enriched at –9.30 to –8.90‰ V-SMOW and reflect a significant Littorina component.

Trace elements: Complete for the selected sample.

General: Na-Ca-Mg-Cl(SO_4-HCO_3) groundwater of brackish marine (Littorina) type. Stability is indicated during sampling; the final sample is considered anomalous and therefore not included in this assessment. There remains some doubt surrounding increased tritium during the last 7 days of sampling; this may be explained by anthropogenic contamination from SFR or other sources such as short-circuiting. This doubt, plus the possibility of some short-circuiting, explains the allocated Category 3 status.

KFM11A (447.50–454.64 m; vertical elevation of –389.68 m)

Borehole KFM11A is 851.21 m long (vertical depth of 716.19 m), cased to 71.60 m and inclined at ~ 60° from the horizontal towards the NE. The borehole was drilled to intersect the Singö zone, a regional deformation zone between the mainland and Gräsö Island. The zone might constitute a discharge area and serve as a hydraulic boundary for the groundwater in the tectonic lens. For this reason, hydrochemical investigations were performed in two sections, one above and other below Singö zone.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)				x	
Drilling water (> 10%)					
Time series (adequate)				x	
Time series (inadequate)					
Time series (absent)					
Suitable section length				x	
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)				x	
Major ions (incomplete)					
Environmental isotopes (complete)					
Environmental isotopes (incomplete)				x	

Differential Flow Log: Measurements only exist to around 500 m borehole length. Three zones of enhanced transmissivity occur at 70–110 m (10^{-5} m^2/s), 250–300 m ($10^{-7.5}$ m^2/s) and 400–450 m (10^{-6} m^2/s), the last mentioned representing the initial part of the Singö DZ. These higher transmissive zones are in general agreement with single hole injection tests carried out at 100 m and 20 m intervals. Natural flow (i.e. no pumping) is dominantly from the bedrock to the borehole with some minor flow from the borehole to the bedrock between 400–430 m. These differential flow measurements were complemented by single hole hydraulic injection tests from 475 m almost down to the bottom of the borehole. Data from these indicate irregular transmissivities ($10^{-9.9}$ to $10^{-6.9}$ m^2/s) as the Singö DZ is penetrated with a marked increase to just under 10^{-6} m^2/s within the NE margin of the DZ.

Electric Conductivity log: Without pumping there is a salinity break at 80–100 m between dilute (~ 1.12 S/m) and more saline water (1.2 S/m) which becomes more apparent with pumping (to 1.8 S/m). Pumping also reveals more minor breaks at around 200 m and 415 m, both showing increase in salinities to 1.85 and 2.0 S/m. These breaks reflect the two horizons of high transmissivity indicated above at 70–110 m and 400–450 m.

Drilling Water: HFM33 (0–140.20 m; major flow input at ~136 m): Na-Ca-Mg-Cl(HCO$_3$, SO$_4$) Littorina-type groundwater (~5,300 mg/L Cl; 251 mg/L Mg) with an enriched Littorina δ^{18}O signature (–8.5‰ V-SMOW). Tritium data suggest some younger, near-surface mixing (1.5 TU). Volume of flushing water used was 959 m^3 and 2,712 m^3 returned, indicating a strong inflow of formation groundwater into the borehole during drilling.

Charge Balance: OK ranging from –1.41 to +0.22%.

Time Series: 2007-01-18 to 2007-03-12 (53 days). Adequate time series but unstable showing a systematic decrease in Cl (4,690–4,210 mg/L) accompanied by small decreases in Na and Ca and increases in HCO$_3$ and Mg (i.e. marine component). Drilling water consistently between 5–10% but incremental decrease with time (12.80–5.88%). Complete major ions.

Isotopes: No ^{14}C or δ^{13}C probably because of the low HCO$_3$ content (8.42 mg/L) in the selected sample; tritium present at 2.6–3.0 TU which is greater than the drilling water and either indicates an additional near-surface input when compared to the drilling water, or some source of contamination (via SFR?). δ^{18}O values (range –12.20 to –11.9‰ V-SMOW) also indicate a small enrichment with time, i.e. possibly due to an increase in marine-type water. The presence of any cold climate component is not obvious.

Trace elements: Absent for the selected sample.

General: Groundwater is Ca-Na-Cl(SO$_4$) brackish non-marine in type. During sampling this groundwater shows a small but significant saline instability indicated by the time-series data suggesting the introduction of near-surface water with a modern Baltic Sea component. Tritium is variable and may be the result of contamination from SFR. These near-surface marine or contamination components are in addition to that known to exist in the drilling water. Selected sample taken close to the beginning of the sampling period aimed at a 'first-strike composition' (e.g. showing a weak depleted δ^{18}O signature of –12.20 9‰ V-SMOW) before pulling in an increasing Baltic Sea component. Allocated a Category 4 due to uncertain groundwater sources probably via short-circuiting close to Singö DZ, combined with the increased tritium content from a suspected contamination source.

References: SKB P-07-100; P-07-177; P-07-85.

KFM11A (690–710 m; vertical elevation of –593.76 m)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)				x	
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)				x	
Time series (absent)					
Suitable section length				x	
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)				x	
Major ions (complete)					
Major ions (incomplete)				x	
Environmental isotopes (complete)					
Environmental isotopes (incomplete)				x	

Drilling Water: HFM33 (0–140.20 m; major flow input at ~136 m): Na-Ca-Mg-Cl(HCO_3, SO_4) Littorina-type groundwater (~5,300 mg/L Cl) with an enriched Littorina $\delta^{18}O$ signature (–8.5‰ V-SMOW). Tritium data suggest some younger, near-surface mixing (1.5 TU).

Charge Balance: OK ranging from –1.34 to +0.03%.

Time Series: 2007-07-11 to 2007-07-16 (5 days). Inadequate time series but nevertheless enough to show a systematic increase in Cl (4,410–5,360 mg/L) accompanied by increases in Na and Ca and a decrease in HCO_3, SO_4 and Mg (i.e. marine component; 115–78.1 mg/L). Drilling water shows an incremental decrease with time from 5.21–3.32% which would be compatible with the decrease in the Littorina component. Complete major ions for the last sample taken in the series. However, incomplete major ions for the most suitable sample (no Fe(tot)/(Fe(II), Mn, S^{2-} or DOC/TOC).

Isotopes: Incomplete; no $\delta^{13}C$ and ^{14}C data; no tritium data. $\delta^{18}O$ values range from –10.70 to –10.00‰ V-SMOW).

Trace elements: Complete for the last sample taken in the series. However, absent for the most suitable sample selected.

General: Generally a significant saline instability shown by the time-series data indicating the gradual removal of the drilling water/Littorina component and increasing brackish non-marine component; continued pumping may have further improved the quality of this sample. Although there are no tritium data, contamination is not suspected to the same extent as level 447.50–454.64 m. Decision made to choose the initial, marine (Littorina?) groundwater type, associated with the Singö DZ as being most suitable. Further sampling indicated the incursion of an increasing component of brackish non-marine groundwater from the surrounding fractured bedrock, probably aided by short-circuiting. This overall uncertainty in mixing plus lack of tritium underlines the allocation of a Category 4 to the sample selected.

KFM12A (343.00–363.00 m; elevation –293.64 m.a.s.l)

Borehole KFM12A is 600.95 m long (vertical depth of 511.93 m), cased to 60.21 m and inclined at ~ 61° from the horizontal towards the NE. The borehole was drilled to intersect the Forsmark Deformation Zone located outside the candidate area to the south-west. The zone is thought to constitute a discharge/recharge area and serve as a hydraulic boundary.

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)					
Drilling water (≤ 5%)					
Drilling water (≤ 10%)			x		
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)			x		
Time series (absent)					
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)					
Major ions (incomplete)			x		
Environmental isotopes (complete)					
Environmental isotopes (incomplete)			x		

Differential Flow Log: No measurements were carried out but single hole hydraulic injection tests were conducted with overlapping sections every 100 m and 20 m from around 50–600 m. These show a fairly regular transmissivity of maximum values around 10^{-6} to 10^{-5} m^2/s down to ~ 400 m, this is followed by a decrease to around 10^{-7} m^2/s to ~ 540 m and a further decrease to < 10^{-9} m^2/s to 600 m.

Electric Conductivity log: No measurements were carried out and no supporting hydrochemical logging has been carried out.

Drilling Water: HFM36 (0–152.55 m; major flow input at ~ 60 m): Na-Ca-Cl(HCO_3, SO_4) type mixed brackish groundwater (~ 1,250 mg/L Cl) with a possible weak marine component (~ 40 mg/L Mg) and a recharge $\delta^{18}O$ signature (–12.4 to –11.8‰ V-SMOW). Tritium data (2.3 TU) suggest some younger near-surface mixing. Volume of flushing water used was 483 m^3 and 543 m^3 returned, indicating a weak inflow of formation groundwater into the borehole during drilling.

Charge Balance: OK at –0.1% for the final sample selected.

Time Series: 2007-04-26 to 2007-05-10 (14 days). Inadequate time series but there is a levelling out of Cl at 3,360 mg/L (i.e. over the last 9 days). Drilling water content constant at around 9.8% during the same 9 day period, after having decreased from an initial 19.8%. Incomplete major ions for the final sampled groundwater selected (no Fe(tot)/Fe(II), Mn, S^{2-} or TOC/DOC).

Isotopes: Incomplete. No ^{14}C or $\delta^{13}C$ data; tritium under detection (< 0.8 TU); $\delta^{18}O$ value at –15.60‰ V-SMOW indicating a strong cold climate input.

Trace elements: Absent.

General: Ca-Na-Cl mixed brackish groundwater with a weak marine component (31 mg/L Mg). Comes under the heading of a ‘brackish glacial’ groundwater comprising components of deeper, brackish non-marine groundwater, glacial melt water, a small marine component and pre-nuclear testing meteoric water. This groundwater type is widespread in the Laxemar area where it is associated with large-scale DZs characterised by both recharge/discharge features. These DZs have retained mixtures of all past groundwater types, i.e. they represent an archive of palaeo-groundwaters. Because these brackish glacial groundwaters are mixtures, the highest category allocated is 3.

References: SKB P-07-121, P-07-171.

KFM12A (516.00–536.00 m; elevation –439.26 m.a.s.l)

Cored Boreholes	**Category**				
Aspects/Conditions	*1*	*2*	*3*	*4*	*5*
Drilling water (≤ 1%)			x		
Drilling water (≤ 5%)					
Drilling water (≤ 10%)					
Drilling water (> 10%)					
Time series (adequate)					
Time series (inadequate)			x		
Time series (absent)					
Suitable section length			x		
Sampling during drilling					
Sampling using PLU hydraulic testing equipment					
Tube sampling					
Charge balance ±5% (±10% for < 50 mg/L Cl)			x		
Major ions (complete)			x		
Major ions (incomplete)					
Environmental isotopes (complete)					
Environmental isotopes (incomplete)			x		

Drilling Water: HFM36 (0–152.55 m; major flow input at ~ 60 m): Na-Ca-Cl(HCO_3, SO_4) type brackish groundwater (~ 1,250 mg/L Cl) with a possible weak marine component (~ 40 mg/L) and a recharge $\delta^{18}O$ signature (–12.4 to –11.8‰ V-SMOW). Tritium data (2.3 TU) suggest some younger near-surface mixing. Volume of flushing water used during drilling is not reported.

Charge Balance: OK at –0.78 to 0.01%.

Time Series: 2007-05-15 to 2007-05-21 (6 days). Inadequate time series but salinity is steady (~ 6,150 mg/L Cl) indicating stability over the 6 day period. Drilling water is low (1.18 to 0.47%) during sampling. Complete major ions.

Isotopes: Incomplete; $\delta^{13}C$ but no ^{14}C despite adequate HCO_3; tritium close to or under detection (< 0.8–1.0 TU); $\delta^{18}O$ values at –12.10 to –11.70‰ V-SMOW.

Trace elements: Complete.

General: Ca-Na-Cl(SO_4) groundwater with a significant marine component (~ 90 mg/L Mg). Therefore, a generally a ‘mixed’ type comprising brackish non-marine, brackish marine and probably old meteoric waters. Allocated Category 3 reflecting a degree of uncertainty due to inadequate time-series data and an environment of groundwater mixing within and close to the major Forsmark DZ.