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Recent geoscientific information relating to deep crustal studies

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January 2004

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Summary

Geoscientific information relating to conditions deep in the earth's crust, as a basis to the deposition of radioactive wastes in vertically drilled boreholes to depths of 4–5 km, has been compiled already in several reports. The objective of this present document is to provide an update of geoscientific information that has become available in the open literature since 1998. Emphasis has been put on crystalline rocks to conform to SKB's disposal concepts for radioactive wastes.

Sammanfattning

Geovetenskaplig information om förhållanden på djupet i jordskorpan har redan tidigare sammanställts i flera rapporter för att tjäna som underlag till att bedöma möjligheten av att deponera radioaktivt avfall i 4–5 km djupa vertikala borrhål. Syftet med det här dokumentet har varit att ge en uppdatering av den nya geovetenskapliga informationen som kommit ut i den öppna litteraturen sedan 1998. Tyngdpunkten har lagts på kristallint berg för att ha bäring på SKB:s förvarskoncept för radioaktivt avfall.

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1 Background

Geoscientific information relating to conditions deep in the earth's crust, as a basis to the deposition of radioactive wastes in vertically drilled boreholes to depths of 4–5 km, has been compiled already in several reports /e.g. Juhlin et al, 1998; SKB, 2000/ and is presently the subject of a review by Nirex UK Ltd /McEwen, in prep/. The objective of this present document is to provide an update of geoscientific information that has become available in the open literature since 1998 for use in the forthcoming FUD 2004 document. Emphasis has been put on crystalline rocks to conform to SKB's disposal concepts for radioactive wastes.

2 Data sources

In addition to the normal geological databases made available through the Geoscience Library at Stockholm University and SGU in Uppsala, the ICDP Website (International Continental Scientific Drilling Programme) provides an excellent global overview of major completed and on-going deep drilling programmes. Whilst many of these programmes are focussed on seismic hazard assessments and volcanic activity close to continental plate boundaries, understanding the genesis of ancient metamorphic belts and investigating meteor impact craters, the completed drilling programmes in Germany (KTB – German Continental Deep Drilling Programme at the western margin of the crystalline Bohemian Massif, culminating in two deep boreholes; one pilot hole to 4000 m and the main hole to 9101 m) and Russia (e.g. The Superdeep Well SG-3 to 12 262 m at Kola, Zapolyarny) provide most of the relevant data of interest to SKB. Some of the results have already been integrated into the earlier compilations, but there remains information from the KTB site presented in a special section of the Journal of Geophysical Research /Haak and Jones, 1997/ which has not been fully evaluated since publication came at a late stage in the preparation of /Juhlin et al, 1998/. Where relevant, this information has been integrated into the present document. In addition, the results of ongoing downhole studies at both the Kola and KTB sites, where there is an active evaluation of new data and also a re-evaluation of existing data, are presented.

Of greater domestic interest is the deep drilling programme (Deep Geothermal Energy Project) presently in progress in the vicinity of Lund. This is financed by Lunds Energi AB and run by the Department of Engineering Geology at the Lund Institute of Technology. One borehole has been drilled to a depth of 3701.80 m with a diameter of 17.5 inches using air-percussion drilling techniques deriving from oil drilling experience in the United States. At the drilled location the lower 1700 m is in crystalline basement rock. Although no drillcore is available, apparently there is considerable hydraulic, hydrochemical and rock stress data information available. Unfortunately, because of confidentiality restrictions no documentation is available yet to the public; an overview report is due to be published in the spring of 2004. In addition, a new borehole is presently being planned.

Many other national programmes are focussed also on Geothermal Energy or Hot Dry Rock (HDR) Technology deep in crystalline rocks (e.g. Swiss Deep Heat Mining Project and many others), but publications, naturally enough, refer mostly to thermal gradient studies and engineering development than to detailed geoscientific information which is sometimes confidential. When possible, information from within this area of development has been included.

A bibliography of some of new reference material is compiled at the end of this report. Not all of this material was directly relevant to the present documentation.

3 New and supporting data

At a recent workshop on deep boreholes and radioactive waste disposal hosted by Nirex, UK, Ltd (2003-09-16), it was reiterated that the 'Distinguishing feature and goal of deep borehole disposal is to get the radioactive waste into the deep stable saline and essentially static deep groundwaters, where reducing chemical conditions and diffusion dominated solute migration are guaranteed'. Based on these pre-requisites, the following presentation of deep geoscientific data will focus on the physical and chemical conditions which are necessary to ensure that these groundwater requirements can be fulfilled.

3.1 General

In crystalline rock because of the rock stress, the fracture frequency, hydraulic permeability and rock porosity are expected to decrease with increasing depth. At a deposition depth of 4000–5000 m groundwater circulation is considered to be static and any movement will be diffusion dominated. At greater depths (or maybe at equivalent depths according to some opinions) petrologists have maintained that the country rock is probably dry due to long-term reaction and consummation of any free fluids. Furthermore, the temperature gradient is considered to increase exponentially and uniformly with depth. This simplistic view, however, has not been borne out fully by the most relevant studies carried out in the Kola and German deep borehole study sites.

3.2 Hydraulic conditions

Advances in the interpretation of reflection seismic studies, for example from the SG-4 borehole (at 5401 m) drilled in the Tagil Volcanic Arc, Middle Urals /Ayarza et al, 2000/ and the SG-3 borehole (at 12 262 m) in the Kola peninsula /Ganchin et al, 1998; Gorbatsevich et al, 2002/, show that many highly reflective zones probably represent fluid filled high porosity intervals, often associated with lithological changes (Figure 3-1). This is in agreement with a comparative study of the Kola SG-3 borehole and the German KTB borehole /Morozov et al, 1997; Smithson et al, 2000/ where seismic interpretation suggests that brines coexist at 12 km at 190°C and 9 km at 265°C respectively; under such circumstances they might have been expected to have reacted. It has been speculated that free fluids might persist to at least 20 km in the upper crust.

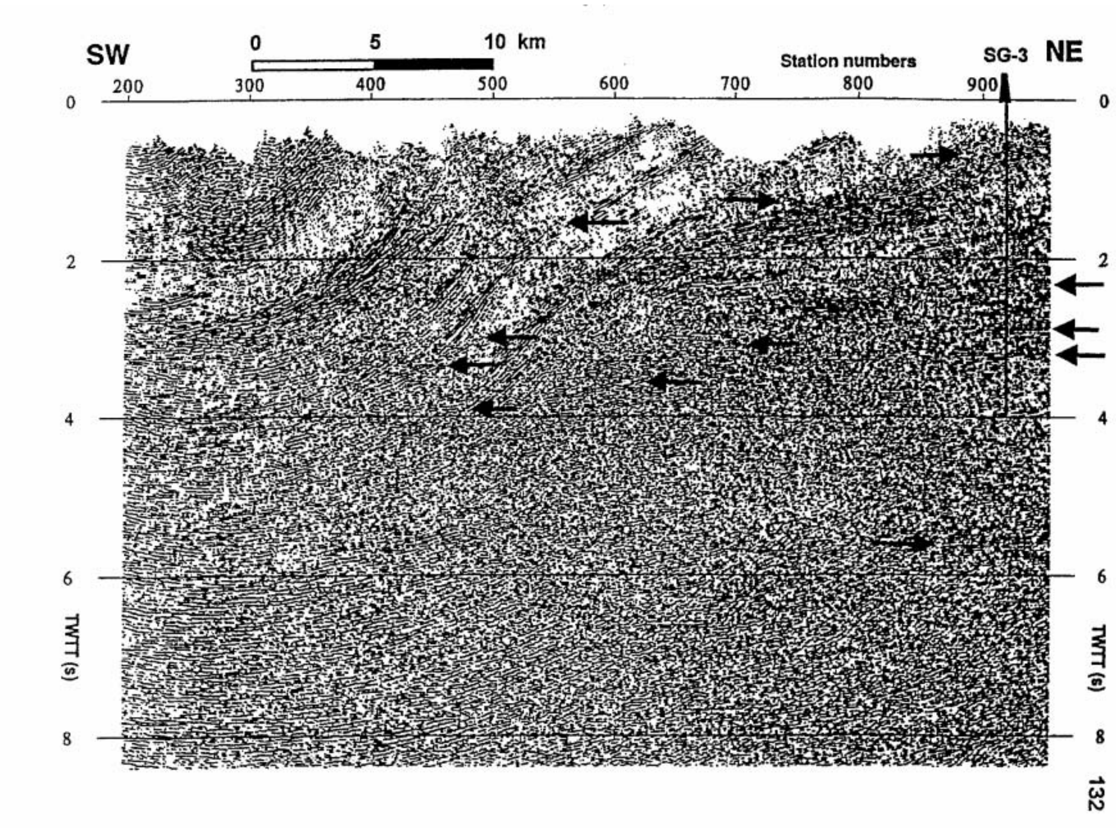

Figure 3-1. Kola SG-3 borehole study: Seismic section showing details of the dipping and sub-horizontal reflections in the upper crust (arrowed). Note the large number of reflections between 1–4 km, many of which are considered to represent fluid filled high porosity intervals /after Ganchin et al, 1998 in Smithson et al, 2000/.

Most of these free fluids or brines appear to be present in microfractures which lack connectivity due to the very low permeability of the host rocks. This was indicated during drilling of the two KTB boreholes when an immediate inflow of brine into the boreholes quickly diminished. Further support of the isolation of these fluids is indicated by the presence of rare gases and helium suggesting the brines to be primitive and free from any modern surface meteoric groundwater contamination. They are considered to consist of a mixture of descending of very old palaeometeoric waters and ascending ancient basement brines /Möller et al, 1997/.

The KTB and Kola drilling programmes also revealed hydraulically conducting fracture systems deep into the bedrock. Earlier work from the KTB site by /Kessels and Kück, 1995/ and more recently by /Huenges et al, 1997/ showed at a depth of 4000 m that hydraulic communication existed between the KTBV 4000 m pilot borehole and the deeper KTBH borehole to 9101 m (Figure 3-2). From this a hydraulic diffusion coefficient constant $D = 0.12\ m^2 sec^{-1}$ was calculated. They concluded that this very extensive hydraulically connected pathway at 4000 km depth in a high brine environment showed that a relatively rapid solute transport in fracture systems is possible. Very detailed study of these brines and coexisting fracture mineralogy revealed that fluid movement has occurred since Cretaceous times and might still occur over distances of tens of kilometres /Möller et al, 1997/.

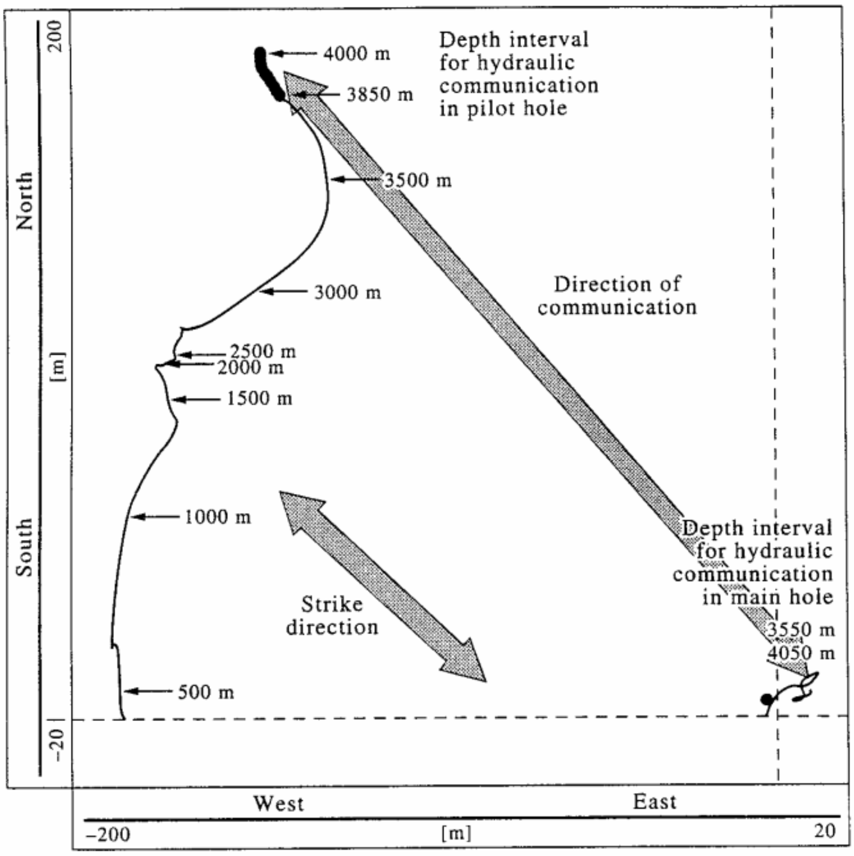

Figure 3-2. *Horizontal projection of the borehole paths for both KTB boreholes showing the major hydraulic connection pathway and the numerous and significant saline fluid inflow zones /after Kessels and Kück, 1995/.*

A further approach to evaluate the hydraulic nature of the KTB host rocks has been the use of in-situ petrohydraulic properties from tidal and barometric analysis of fluid level variations in the two KTB boreholes /Schulze et al, 2000/. The fluid level in the KTBV 4000 m borehole showed a clear tidal signal which allowed the calculation of the areal strain sensitivity. The KTBH 9101 m borehole did not register any tidal or barometric signal which was explained by some obstruction at depth.

The rock permeability at the KTB site was determined as part of the geohydraulic studies /Huenges et al, 1997/. These entailed both in-situ downhole hydraulic and fluid tests and also laboratory petrophysical measurements where porosity, internal surface of the pore space volume, number of fractures, and permeability were determined on recovered drillcore material. On a few cores even permeability was measured under simulated in-situ conditions. The results from the laboratory studies (Figure 3-3) showed that the average permeability parallel to the rock foliation was in the order of 1.4 x 10^{-19} m^2 and perpendicular to the foliation was one order of magnitude lower. The in-situ downhole hydraulic tests (Figure 3-4) gave values of 10^{-17}–10^{-16} m^2 down to 6000 m; specific injection tests from approx. 6000–7500 m gave 10^{-19}–10^{-18} m^2 and from approx. 8000–9000 m gave 10^{-20}–10^{-19} m^2.

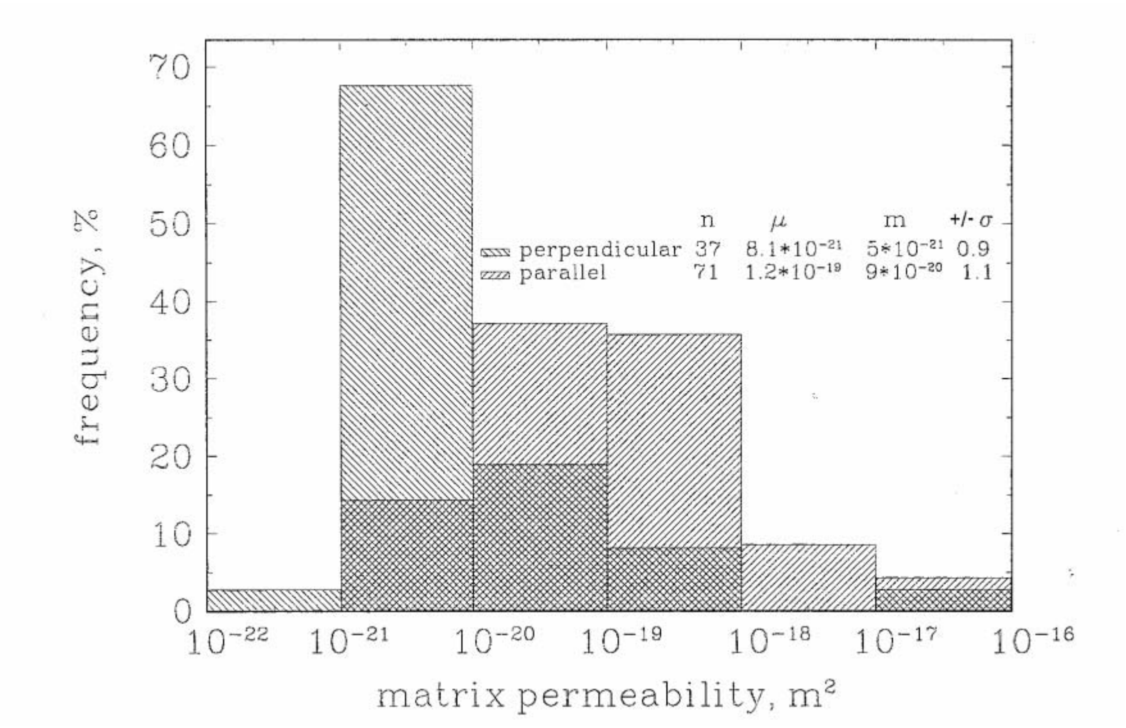

Figure 3-3. *Permeability of rock core material (gneisses and amphibolites) from 4 km (KTBV) and 7.4 km (KTBH) depth measured parallel and perpendicular to the rock foliation. Here n is the number of measurements, μ is the geometric mean, m is the median, and σ is the logarithm of standard deviation /after Huenges et al, 1997/.*

To summarise, the most important conclusion from the physical state of the fluids and hydraulic properties of the rocks analysed at the KTB sites is that the formation pressure remains hydrostatic down to depth of 9000 m (i.e. the base of the KTBH deep hole). Groundwater movement is restricted to fracture zones and the rock matrix essentially represents a closed system.

At the Kola SG-3 borehole the geothermal properties of the rock mass have been applied to further understand the hydraulic properties deep in the bedrock /Popov et al, 1999/. For example, the heat flow density (HFD) was estimated from new measurements of thermal conductivity and the equilibrium temperature gradient was determined also. By analysing the temporal variations of the equilibrium temperature gradient during the return of the borehole to thermal equilibrium following completion, together with experimental results, it was possible to calculate the rock permeability to be around (1 to 3) x 10^{-13} m^2 over the 1–2 km zone if exogenic fracturing is assumed. The authors proposed that the observed vertical variations in HFD were due to movement of fluids in the rock mass in some cases resulting in non-stationary fields (cf Figure 3-7). In particular, the largest geothermal anomaly at 0–2 km depth is caused by a downward movement of meteoric groundwaters in the zone of active water exchange. An abrupt change in HFD at 1.7–2.2 km was attributed to a downward movement of fluids along inclined fracture zones at lithological boundaries. It was suggested that such movement might be the result of post-glacial uplift of the Baltic Shield and would continue as the lateral pressure in deep faults decreases /Popov et al, 1999/.

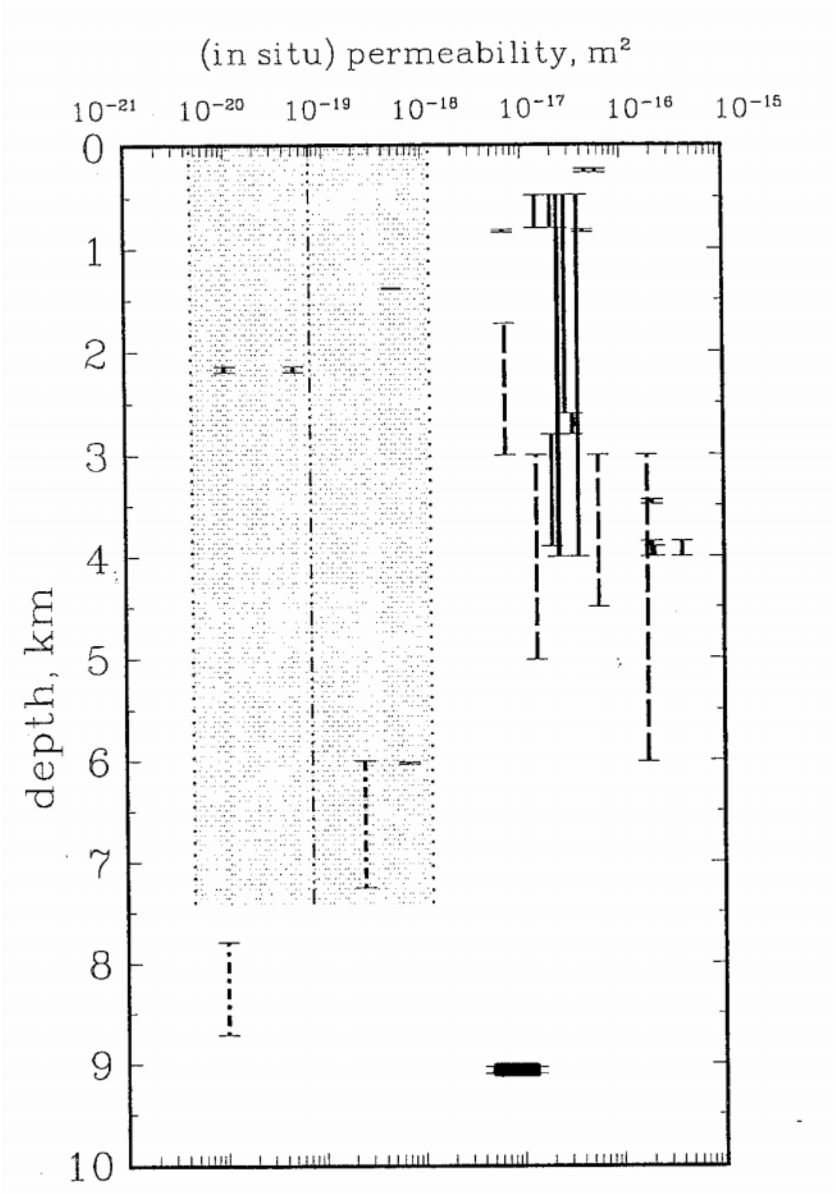

Figure 3-4. Downhole permeability measured in the KTBV and KTBH boreholes – solid vertical lines represent build up hydraulic tests in the KTBV borehole and dashed lines in the KTBH borehole; dotted-dashed lines represent injection tests in the KTBH borehole. The shaded area gives the variance of core permeability (laboratory measured) with the geometric mean value given /after Huenges et al, 1997/.

3.3 Geothermal conditions

3.3.1 Thermal conductivity

The thermal conductivity profile is very much dependent on the rock mineral composition (e.g. lithological differences), specific structural and textural features (including anisotropy) and occurrence of fracture zones and their frequency. Determination of thermal conductivity was carried out in the Kola SG-3 borehole /Popov et al, 1999/ and also in the Vorotilovo borehole to 5374 m depth in the East European Platform /Popov et al, 1998/. In the former over 8000 core samples were measured and in the latter 3715 samples; the measurements were performed on air-dry and fluid-saturated core samples and procedures included optical scanning (some with a laser setup) which is non-destructive and the results compared with more classical methods.

Figures 3-5 and 3-6 show the respective thermal conductivity profiles for the Kola and Vorotilovo boreholes. The Kola profile is quite uniform to 2000 m when a slight increase occurs, evening out until a significant reversal occurs at around 5000 m depth; this is followed by a small but continuous decrease to the hole bottom. In contrast, the Vorotilovo profile (Figure 3-6) increases markedly to around 800 m whereupon the increase is less marked to around 2000 m. Here there is a sharp increase which quickly evens out; to the hole bottom the thermal conductivity is very erratic although a general small increase in trend can be observed. In both profiles there are obvious ‘boundaries’, especially in the Vorotilovo borehole where, for example, at 550, 900, 1900, 3300, 2400, 3700 and 4500 m there are distinct breaks. These ‘thermophysical block boundaries’ correspond to lithological limits, indicating the sensitivity of thermal conductivity to changes in mineral composition, structural features, degrees of cataclasis, brecciation and thermal transformation of rocks. Down to 1900 m in the Vorotilovo borehole porosity is shown to be the main factor that affects the rock thermal conductivity. Rock core measurements show that the open porosity decreases with depth and is very significant in the upper 1500 m.

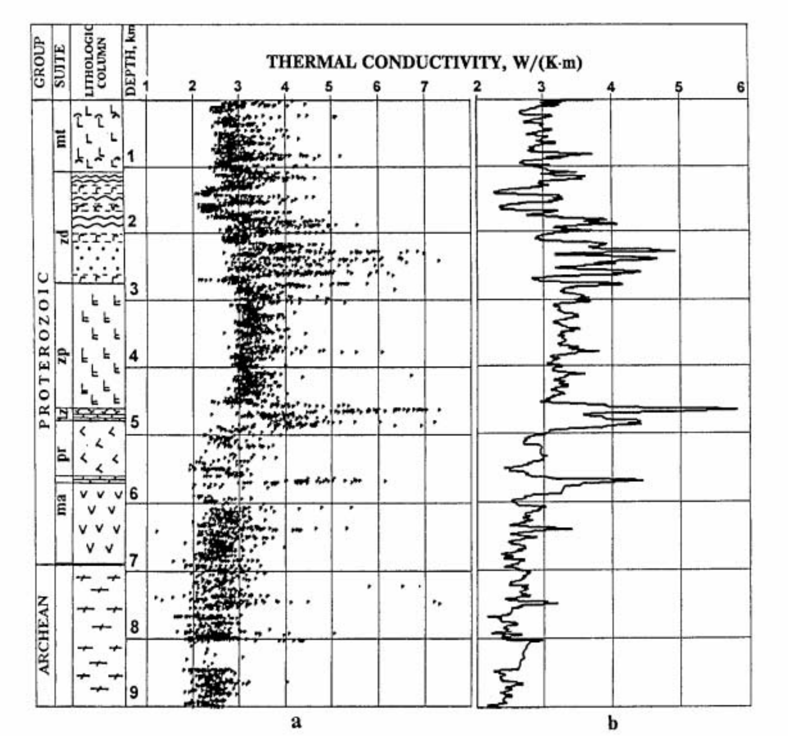

__Figure 3-5.__ Results of rock core thermal conductivity measurements from the Kola SG-3 borehole under normal P-T conditions /after Popov et al, 1999/.

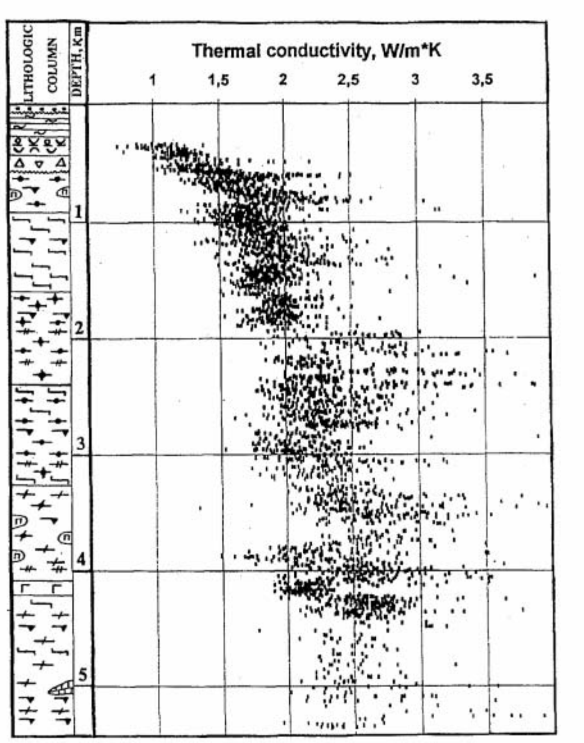

__Figure 3-6.__ Results of rock core thermal conductivity measurements from the Vorotilovo borehole under normal P-T conditions /after Popov et al, 1998/.

3.3.2 Heat flow density

Thermal conductivity data are commonly used to estimate the heat flow density (HFD) which can provide added information about the thermal regime in the earth's crust. A compilation of old and new data from the Kola SG-3 borehole is given in Figure 3-7 after /Popov et al, 1999/.

As would be expected, Figure 3-7 shows a general similarity with the thermal conductivity profile presented in Figure 3-5. Identified are a series of vertical variations in HFD which relate to movement of fluids in the rock, in some cases resulting in non-stationary fields. As already described in Section 3.2, the largest geothermal anomaly at 0–2 km is caused by a downward movement of meteoric waters (2–3 cm/yr at the depth interval 1.7–2.2 km) in the zone of active water exchange.

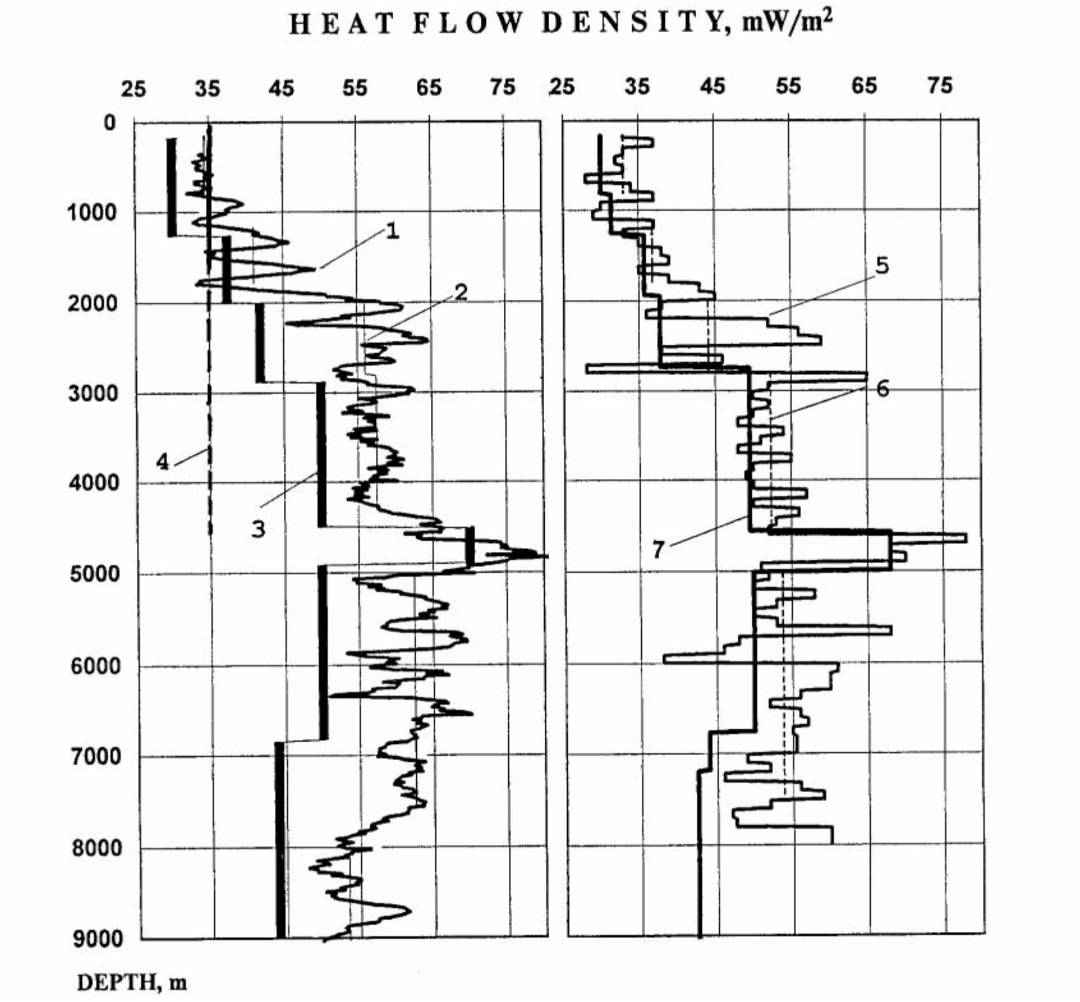

Figure 3-7. Compilation of heat flow density data from the Kola SG-3 borehole; numbers relate to different data sources /after Popov et al, 1999/.

3.3.3 Temperature gradient

Temperatures are expected to increase with depth and Figure 3-8 from the Kola SG-3 borehole reflects this trend /Popov et al, 1999/. The data are from downhole measurements taken over periods of several years; the deviations or non-equilibrium values are due to several reasons, for example artefacts from higher drilling fluid temperatures which take time to re-equilibrate. In general, the upper part of the bedrock is most sensitive to thermal disturbances during drilling. On a positive note, these temporal variations in the temperature over a given depth interval can give important information on the structure and hydrogeological regime of the bedrock and the processes of heat transfer within it.

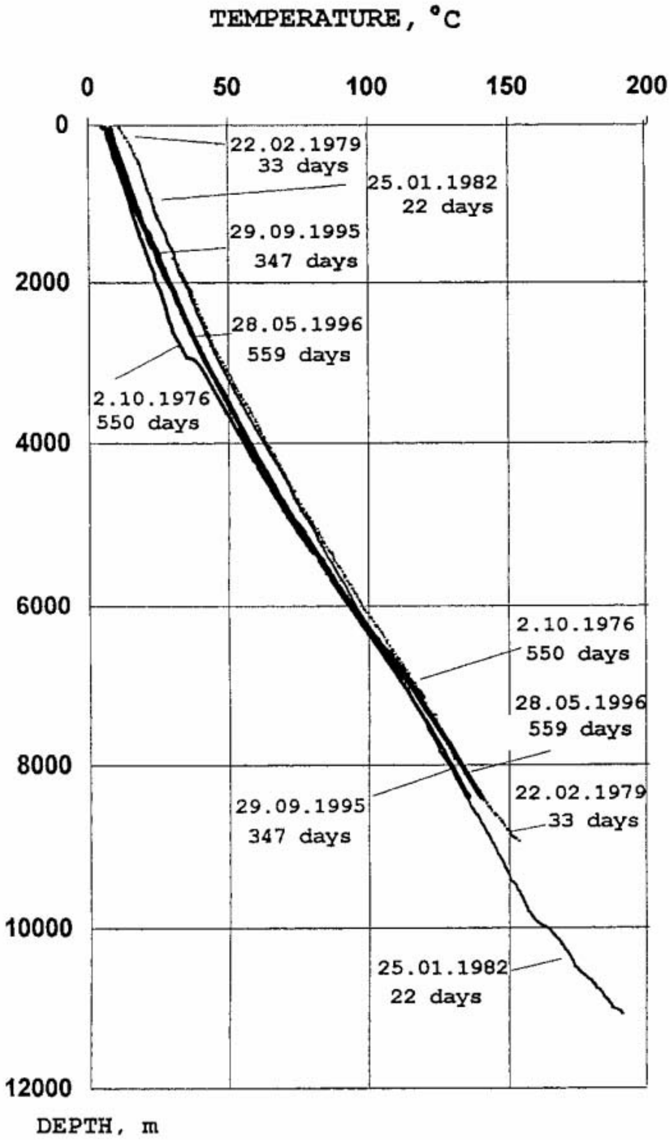

__Figure 3-8.__ Temperature logs recorded at various depths from the Kola SG-3 borehole and the duration of the borehole standing /after Popov et al, 1999/.

Since geographically and geologically the Kola region shows close similarities to the Swedish basement bedrock, Figure 3-8 is probably a good approximation to expected temperature conditions at the repository depths being considered in Sweden.

From the Kola data, predicting the temperature gradient at increasing depth may not seem to be a major problem, and problems were not foreseen at the outset of the German KTB drilling programme. At an early stage in the KTB investigations shallow boreholes were drilled at the site and the derived geothermal data were evaluated to predict the temperatures expected to be found at greater depth. However, when the geothermal data were being evaluated from the shallower KTBV borehole at 4000 m the highly unexpected result was that the thermal gradient and the vertical heat flow density only met the predicted values in the upper 1000 m /Emmermann and Lauterjung, 1997/. For example, at 4000 m depth the measured temperature of 119°C lay well above even the upper error limit calculated from the data obtained from the shallow-drilling geothermal studies.

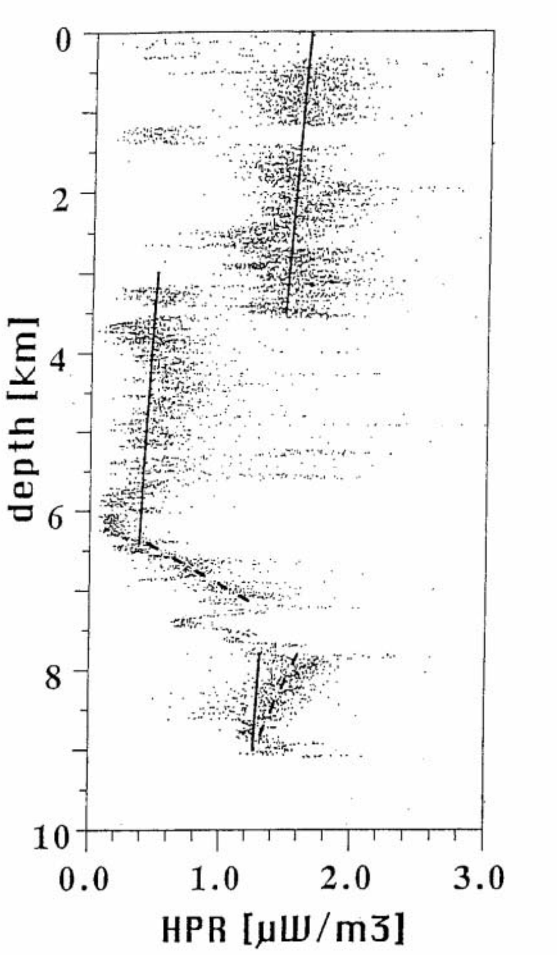

__Figure 3-9.__ KTBH borehole: Diagram showing the changes in heat production values from laboratory experiments and downhole measurements /after Emmermann and Lauterjung, 1997/.

These conclusions were consistent with the KTBH or super deep borehole, where in the upper 0–1500 m the temperature gradient increased from 20 K/km to around 28 K/km at 1500 m and remained at that value to the final depth at 9100 m. The undisturbed equilibrium temperature at this maximum depth is about 265°C /Clauser et al, 1997; Wilhelm, 2000/.

Furthermore, the heat production distribution with depth closely reflects lithological variations (Figure 3-9). Although the data show an overall slight decrease with depth, they do not conform to the generally accepted exponential decrease with increasing depth.

3.4 Hydrogeochemical conditions

As concluded from earlier evaluations /Juhlin et al, 1998/, the upper 1000 m of crystalline bedrock of Baltic Shield type represents the average maximum penetration of surface derived meteoric groundwaters, although it is important to point out that the penetration depth is very much dependent on the hydraulic properties of specific fracture systems. At greater depths highly saline to brine compositions prevail. Additional recent studies confined to around 1000 m depth, for example representing the Finnish and Swedish site characterisation programmes at Olkilouto /Pitkänen et al, 1999/ and now at Forsmark and Simpevarp/Laxemar /Laaksoharju et al, 2004/, generally support the penetration of meteoric derived groundwaters (e.g. of glacial melt water origin) to at least 1000 m. This 1000 m cut-off, however, may in some cases be more a function of the restricted depth of the boreholes than the limit of active meteoric groundwater exchange. For example, the Kola SG-3 borehole to 12 262 m, shows active meteoric water exchange to at least 2 km /Popov et al, 1999/ and may even to 4 km /NEDRA, 1992/. However, this is not reflected in the two KTB boreholes to 4000 m and 9101 m where no ‘recent’ meteoric groundwater exchange has been observed. Here the fluids result from a mixing of downward moving ancient palaeowaters and ascending basement brines of even greater age; the apparent gas accumulation times for ^{4}He and ^{40}Ar in these groundwater mixtures yield ages of 15–80 Ma and 30–300 Ma respectively /Möller et al, 1997/. The distribution of these noble gases and molecular N_2 with depth is shown in Figure 3-10, where for N_2 and the He/Ar ratio a clear lithological influence (i.e. amphibolites vs gneisses) is apparent at around 3000 m depth.

From the KTB site /Möller et al, 1997/ has related the chemistry of these free brine fluids to a detailed examination of the fracture mineralogy and their fluid inclusions, and also to the chemical and isotopic composition of rocks and minerals to 9101 m. This allowed the reconstruction of the palaeofluid evolution, their migration pathways and sources. Basically, aqueous fluids were largely lost during the Devonian amphibolite facies metamorphism. Thereafter, radiogenic, nucleogenic and fissiogenic gases, together with NH_4-fixed nitrogen, were released from host rocks and partly included in secondary fluid inclusions. During the Hercynian uplift Na-Cl fluids (formation water) infiltrated and dissolved noble gases and N_2 largely originated from the host rocks. In the course of the Cretaceous denudation, high salinity Ca-Na-Cl brines, possibly derived from Permo-Carboniferous sediments but altered by fluid/rock interaction, migrated into their present position. The similarity of these brines and their isotopic composition with the ancient and deep Canadian Shield brines has been noted also (Figure 3-11).

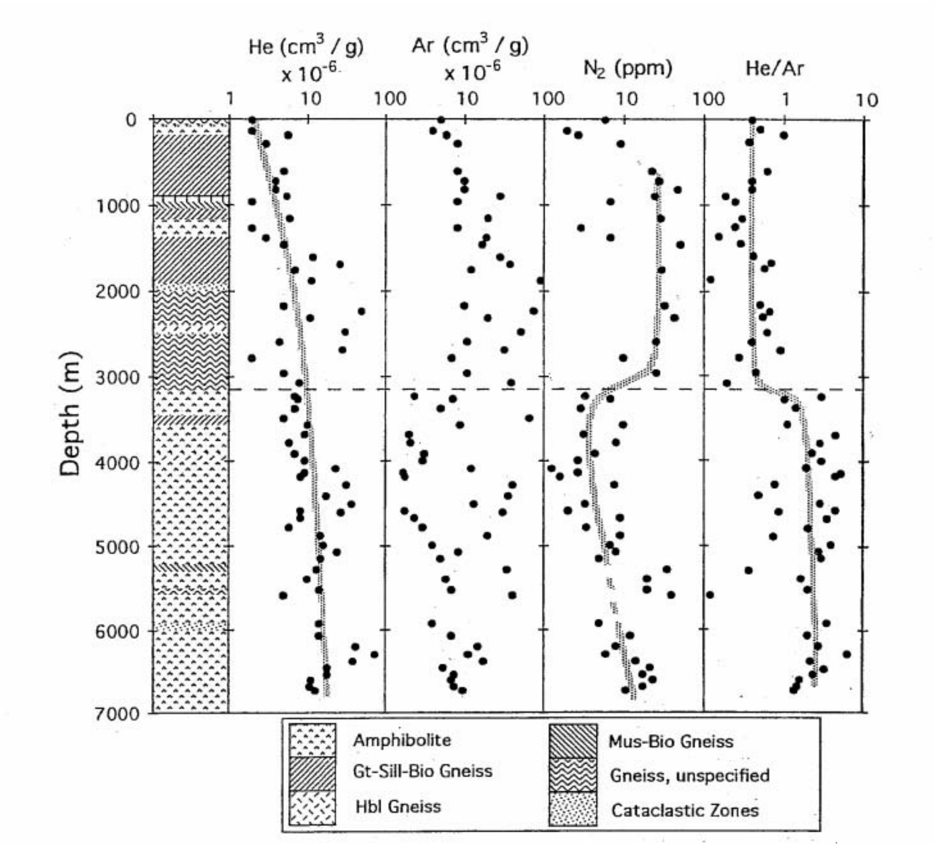

Figure 3-10. *Variation of He, Ar and N_2 released from rock samples with depth. Shaded lines represent the trends with depth /after Möller et al, 1997/.*

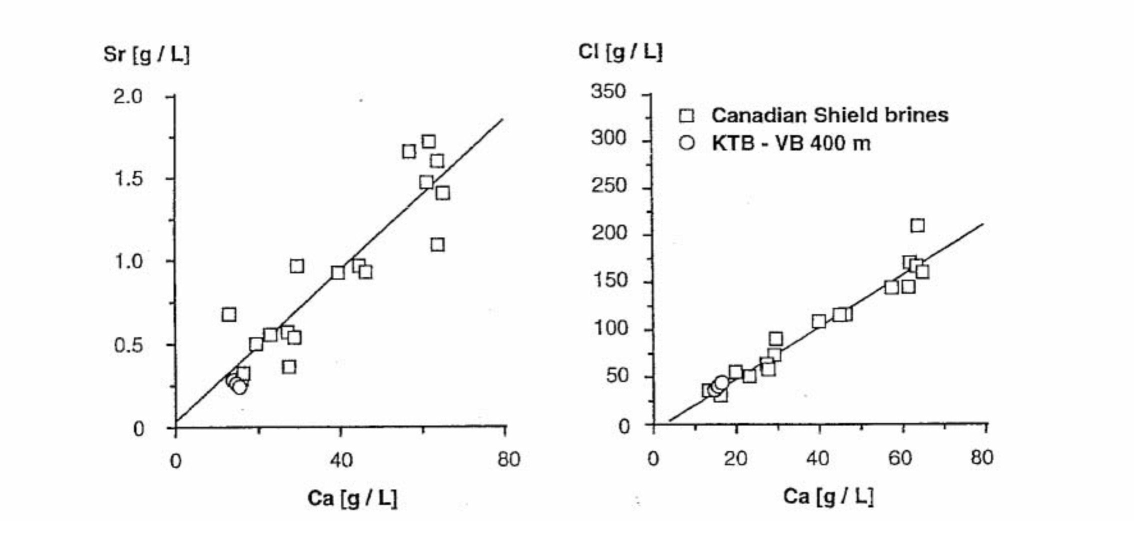

Figure 3-11. *Ca/Sr and Ca/Cl ratios comparing the Canadian Shield brines with those from the KTBV borehole /after Möller et al, 1997/.*

Deep saline groundwaters in granites have been studied from the European Hot Fractured Rock (HFR) site in Alsace, NE France, where two boreholes have been drilled; GPK1 (to 3590 m) and GPK2 (to 5000 m) /Rabemanana et al, 2003/. Samples collected from these two depths are characteristic of brines with TDS contents > 100 g/kg and an ionic strength of 1.65. Recalculation of the mean fluid compositions, assuming that they are in equilibrium with the contact mineral assemblages, are given in Table 3-1.

Table 3-1. Mean fluid compositions recalculated from the chemical analyses /Rabemanana et al, 2003/

Composition (mmol kg^{-1})	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe^{2+}	SiO_2	Cl^-	S	C
3.8 km depth	993	80.8	160	5.42	0.501	2.17	1460	2.19	40.1
5 km depth	1079	68.5	157	3	2.4	5.7	1452	1.6	19

Fluid at 3.8 km depth (T = 165°C, pH ~ 4.78)
Fluid at 5 km depth (T = 200°C, pH ~ 4.9)

3.5 Bacteriological activity

Bacteria-mediated reactions may result in short- and long-term hydrochemical changes (e.g. due to the presence of sulphate-reducing species) in the near-field environment of a KBS-3 type radioactive waste repository located at around 500 m depth. Would similar problems arise in a deep hole repository at 4000–5000 m? In /Juhlin et al, 1998/ and /SKB, 2000/ the existence of bacteria down to 1500 m was noted, and the potential of even deeper occurrences could not be ruled out /Kaiser, 1995/. The borehole windows into super deep environments are still very few and none has been drilled with microbiology in mind. However, it would appear that depth alone is not the limiting factor for evidence of life, but rather temperature. For example, the KTBV borehole at 4000 m was sampled at this depth for hyperthermophiles in fluids representing a temperature of 118°C, but culturing of life microorganisms was unsuccessful /Seifer, 2000/. Apparently the highest culturing temperature for hyperthermophiles has not exceeded 113°C. In contrast, the Gravberg-1 borehole at 6800 m depth was sampled at 5278 m at a temperature of 65–75°C and thermophilic bacteria were successfully enriched and isolated /Pedersen, 2001/.

The existence of microbial life associated with geothermal systems has been reviewed recently by /Sand, 2003/. This focussed on the consequences of biocorrosion and biodeterioration within the geothermal energy industry, but clearly such microbial activity at temperatures less than 116°C may have some bearing on borehole casing materials and other engineered materials (e.g. metal canisters) used in deep disposal concepts. Mentioned was the production of inorganic acids as an end product of microbe metabolism, for example nitric and sulphuric acid, although only very specialised lithoautotrophically growing bacteria are able to produce these products. Furthermore, organic acids are an excretory product which may react with engineered materials.

Of some peripheral interest to microbiological activity at depth is the proposed DAFSAM (Drilling Active Faults in South Africa Mines) project under the auspices of the ICDP (International Continental Scientific Drilling Programme). The main objective is to characterise the near-field behaviour of active faults before, during and after earthquakes. This is an essential safety precaution in the deep gold mines of South Africa where sudden triggering of rock stress has resulted in many fatalities. Some of the scientific questions posed are: Do seismic events trigger biological and chemical activity within deep faults? Is there a critical pore size or minimum size of interconnected pore volume necessary to sustain viable microbial communities? Do microbial communities populating the pores of the rock matrix differ from those in fissure water? Do new high free energy surfaces created during faulting facilitate intense secondary mineralisation and population by microbes? Drilling from underground sites to around 4000 m plus will provide access to continuous cores and the on-site analysis of the solid, fluid and microbial content of the core immediately following core extraction will minimise contamination and pore water degassing, ensuring the anaerobic conditions necessary to sustain certain life forms. This project commenced in 2003 and is scheduled to continue to 2007.

3.6 Rock mechanical properties

3.6.1 Petrophysical and mechanical properties

Laboratory tests of physical and mechanical properties /Trčkova et al, 2002/ were performed on amphibolites representing two rock units from the Kola SG-3 borehole; Proterozoic (at 3043 m and 3530 m) and Archean (at 7951 m, 8942 m and 9904 m). Obtained grain density and bulk density were nearly identical for all samples but porosities increased slowly with depth. Marked strength differences were found between amphibolites from the two rock units which were explained by the variable grain-size distribution and by the spatial arrangement of the main rock-forming minerals. Most importantly, these properties were also influenced by stress-release mechanisms due to rock recovery from great depths. Such a sampling artefact may explain adequately the observed increase in porosity with depth, thus underling the necessary caution to be taken when interpreting such data.

3.6.2 Borehole breakouts and in-situ rock stress

Borehole breakouts are enlargements and elongation of a borehole in a preferential direction and are formed by spalling of fragments of the well bore in a direction parallel to the minimum (least) horizontal stress. These breakouts are commonly used to determine the state of stress on a local and even regional scale, particularly the nature of the stress fields with depth and the associated implications for deep borehole stability. Such data were used in the Gravberg-1 borehole but proved inconclusive /e.g. Juhlin, 1990/. A more recent interpretation by /Zajac and Stock, 1997/ suggested that the data indicated a thrust faulting stress state at depth. This has been disputed by /Lund and Juhlin, 2000/ who reiterate that the breakout data at Gravberg-1 are inconclusive. They suggest that the Siljan stress state below 1 km depth is best described by a strike-slip faulting regime (Figure 3-12).

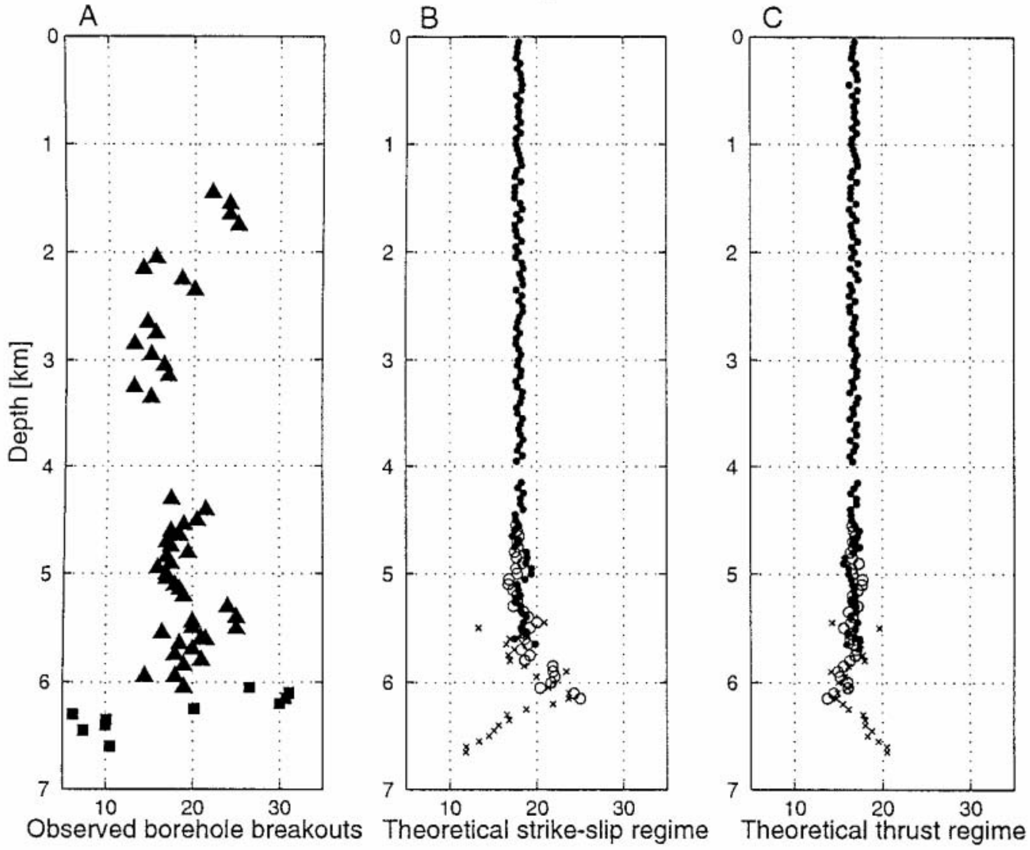

Figure 3-12. *Gravberg-1 borehole: Borehole breakouts, azimuth in degrees east of north. a) Breakout data, b) Strike-slip regime as interpreted by /Lund and Zoback, 1999/, and c) Thrust regime as interpreted by /Zajac and Stock, 1997/.*

To estimate the maximum horizontal in-situ stress from logged borehole breakout dimensions demands knowledge of the true triaxial compressive strength of the medium. To this end laboratory measurements simulating bedrock conditions were carried out on impermeable amphibolite samples from the German KTBH borehole selected from depths of 3200–7800 m /Haimson and Chang, 2002/. Results showed that the maximum horizontal stress increases steadily with depth confirming previous assessments of a strike-slip stress regime, similar to that suggested above for Gravberg-1 by /Lund and Juhlin, 2000/

3.7 General conclusions and relevance to a deep hole repository

These conclusions are arranged under various headings of importance with respect to deep hole disposal of radioactive wastes at 4000–5000 m depth:

Geothermal considerations

- The rock thermal conductivity is an important parameter to help dissipate the heat generated by the waste package and depends on rock composition.
- In this respect, since mafic-rich varieties are more conductive, a granitic host rock may be considered more problematic.
- Fractures tend to increase the thermal conductivity; however due to the rock stress the frequency of fractures decreases with depth so that a deterioration in thermal conductivity with depth is to be expected.
- Evaluating the temperature/heat production gradient is an important pre-requisite for disposal, for example the long-term stability of engineered materials. The experience from the German KTB programme has underlined that it may not always be possible to extrapolate near-surface derived predictions of temperature variations to repository depths, especially in a heterogeneous bedrock environment.

Hydraulic conductivity

- Main problems are the presence of gas phases and groundwater flow; of lesser importance is fluid circulation initiated by the temperature gradient resulting from the temperature increase of the waste package.
- Rock permeability is expected to be in the order of (1 to 3) x 10^{-13} m^2 over a 1–2 km zone if exogenic fracturing is assumed, in the order of 10^{-17}–10^{-16} m^2 at repository depths, and in the order of 10^{-20}–10^{-19} m^2 at still greater depths.
- This reduction in permeability is matched by a reduction in porosity.
- In areas of subdued topography (e.g. typical Baltic Shield terrain), a zone of active downward moving meteoric water exchange exists in the upper 0–2 km; at greater depths the highly saline fluids and brines are extremely ancient and no recent meteoric water input is observed.
- In areas of more extreme topography (e.g. the Gravberg-1 site close to the Swedish uplands to the west) the zone of active meteoric recharge may reach 4–5 km before highly saline fluids are encountered.
- At the KTB site highly saline fluids appear to be present throughout the rock matrix to at least 9 km. Most, however, are present in microfractures which lack connectivity due to the very low permeability of the host rocks and therefore do not participate in any active groundwater circulation.
- If hydraulic circulation is indicated at favourable fracture zones of higher hydraulic conductivity, the presence of highly saline to brine fluid compositions may be expected to minimise such circulation.
- Evidence shows that active saline groundwater circulation does exist but is restricted to intermittently occurring hydraulically conductive fracture zones. Nevertheless at some locations (i.e. the KTB site) it was concluded that in a high brine environment relatively rapid solute transport in fracture systems is possible.

Hydrogeochemistry

- At repository depths long-term hydrochemical stability appears to be assured where hydraulic conditions are favourable (i.e. low topography; weak hydraulic gradients; low permeability).
- This is further supported by the presence of highly saline fluids to brines and associated gases at great depths which reveal ages of millions of years with no evidence of recent meteoric water exchange.
- Fracture mineral chemistry and fluid inclusion studies support long-term stability.
- Highly saline fluids, whilst undesirable from a near-field viewpoint (e.g. corrosion potential), are less conducive to radionuclide mobilisation and transport.
- Solute transport through the bedrock will be diffusion dominated provided major hydraulically conductive fracture zones are avoided.

Microbial activity

- The potential for microbial activity appears to be feasible in the Baltic Shield bedrock environment as it is unlikely that the temperature threshold of 115°C will be exceeded at repository depths, i.e. the temperature above which life microoganisms cannot be sustained. However, provided major hydraulically conductive fracture zones are avoided (i.e. potential sources of microbes and nutrients), microbial activity may not be an important issue.

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