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Review of geoscientific data of relevance to disposal of spent nuclear fuel in deep boreholes in crystalline rock

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Summary

In this report a compilation of recent geoscientific data of relevance to disposal of spent nuclear fuel in deep boreholes in Sweden is presented. The goal of the study has been limited to identifying and briefly describing such geoscientific information of relevance to disposal in deep boreholes that was not available at the time when previous compilations were made. Hence, the study is not to be regarded as a general up-date of new geoscientifec information.

Disposal of spent nuclear fuel in deep boreholes has been studied in Sweden since the second half of the 1980s. The currently studied concept has been proposed by Sandia National Laboratories in the USA. In this concept the spent fuel elements are encapsulated in cylindrical steel canisters that are joined together in strings of 40 canisters and lowered into five kilometres deep boreholes. Ten such strings are stacked between three and five kilometres depth separated from each other by concrete plugs.

The study started with a review of boreholes that have been reported after the previous reviews that were published in 1998 and 2004. A total of 12 boreholes of potential relevance were identified. Further study showed that only four out of these holes penetrated into crystalline rock. Two of these were deemed to be less relevant because they were drilled in areas with much higher geothermal gradient than in the parts of the Fennoscandian shield that realistically could host a Swedish deep borehole repository. Of the two remaining boreholes, only one, a geoscientific hole drilled at Outokumpu in Finland, is associated with a reasonably complete geoscientific data set. It is worth mentioning that a large part of this hole is drilled through metasedimentary rock (mica schist) rather than granitic rock.

The information collected and reviewed has been gathered under the headings hydraulic conditions, geothermal conditions, hydrogeochemical conditions, bacteriological activity and rock mechanical properties. Only from the hole at Outokumpu is there information under all headings.

A general conclusion is that data available from deep boreholes demonstrate that there are conductive fractures also at depth. However, the hydrogeochemistry and isotope data suggest that the water in these fractures has been isolated from surface processes for a very long time. Despite this, it appears that the origin of these deep groundwaters is ancient meteoric water rather than fluid inclusions. The deep waters are generally saline, but the salinity varies in a non-regular fashion. Thus, the present study confirm the conceptual picture from the previous studies that the saline groundwater found below a halocline located at 1–2 kilometres depth in flat areas with crystalline rock is virtually stagnant. The results from the Outokumpu hole seem to more clearly explain the origin of the salinity in the deep groundwater than the earlier studies.

Sammanfattning

I denna rapport redovisas en sammanställa nytillkommen geovetenskaplig information av relevans för deponering av använt kärnbränsle i djupa borrhål i Sverige. Studiens målsättning har varit begränsad till att identifiera och översiktligt beskriva sådan geovetenskaplig information av relevans för deponering i djupa borrhål som inte fanns tillgänglig när tidigare sammanställningar gjordes. Studien utgör således inte någon allmän uppdatering av ny geovetenskaplig information.

Deponering av använt kärnbränsle i djupa borrhål har studerats i Sverige sedan andra halvan av 1980-talet. Under denna period har flera utformningskoncept föreslagits. Det nu analyserade konceptet för deponering i djupa borrhål har föreslagits av Sandia National Laboratories i USA. I detta koncept kapslas bränslet in i kapslar av kolstål. Vid deponeringen fogas kapslarna samman med kopplingar till strängar om 40 kapslar och sänks ner i fem kilometer djupa borrhål. I ett borrhål deponeras tio sådana kapselsträngar separerade av betongpluggar.

Denna studie började med en inventering av borrhål som har rapporterats efter slutförandet av tidigare studier. Av de totalt 12 borrhål som identifierades vara av potentiell relevans var det bara fyra som åtminstone delvis borrats i kristallint berg. Av dessa bedömdes två vara av mindre relevans eftersom de hade anlagts i områden med mycket högre geotermisk gradient än vad som förekommer i de delar av den Fennoskandiska urbergsskölden som skulle kunna komma i fråga för slutförvaring i djupa borrhål i Sverige. Av de kvarvarande två borrhålen är det endast ett som har bidragit med någorlunda kompletta geovetenskapliga data, nämligen ett geovetenskapligt borrhål vid Outokumpu i Finland. Det kan vara värt att notera att huvuddelen av detta hål har borrats genom metasedimentärt berg (glimmerskiffer) och inte genom granitiskt berg.

Den insamlade informationen har sorterats under rubrikerna hydrauliska förhållanden, geotermiska förhållanden, hydrogeokemiska förhållanden, bakteriologisk aktivitet och bergmekaniska egenskaper. Endast hålet i Outokumpu har bidragit med information under alla rubrikerna.

En allmän slutsats är att tillgängliga data visar att det finns vattenledande sprickor även på stora djup. Hydrogeokemiska data och isotopdata indikerar dock att vattnet i dessa sprickor inte har varit i kontakt med ytliga system på mycket länge. Trots detta förefaller vattnets ursprung vara gammalt meteoriskt vatten. Generellt kan sägas att det djupa grundvattnet har en hög salthalt men att salthalten varierar på ett icke regelbundet sätt. Dessa resultat bekräftar den konceptuella bilden från tidigare studier att det salta grundvattnet under ett språngskikt på 1–2 kilometers djup är i huvudsak stagnant. Resultaten från Outokumpuhålet ser dock ut att tydligare än tidigare studier förklara saltets ursprung.

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1 Introduction

The objective with the present document is to provide an update of geoscientific information of relevance to disposal of spent nuclear fuel in deep boreholes in Sweden. The goal of the study has been to identify and briefly describe relevant geoscientific information that has become available since a previous appraisal by Smellie (2004). The appraisal by Smellie, in turn, was an update of a study by Juhlin et al. (1998). It should be noted that the present study is focusing on information of relevance to disposal in deep borehole and, hence, is not intended to constitute a general study of new geoscientific information. It should also be noted that drilling the drilling experience from the sites investigated has not been included in the present study. In a parallel study by Odén (2013) a comprehensive analysis of the prerequisites for drilling deep disposal holes in crystalline rock is given.

In the following sub-sections a brief description of disposal of spent nuclear fuel is given followed by a summary of the findings in Smellie (2004). In Chapter 2 a selection of boreholes with the potential to yield data of relevance to disposal in deep boreholes is made. The data and information available from the relevant boreholes is collated in Chapter 3. Finally the findings from the study are discussed in Chapter 4.

1.1 Disposal of spent nuclear fuel in deep boreholes

SKB has since the second half of the 1980s performed several studies of disposal of spent nuclear fuel in deep boreholes. A design concept for deep borehole disposal was developed and evaluated against other alternative disposal methods in the Pass project (Birgersson et al. 1992, SKB 1992). This concept has been analysed from different perspectives (e.g. Juhlin and Sandstedt 1989, Juhlin et al. 1998, SKB 2000, Harrison 2000, Smellie 2004, Grundfelt and Wiborgh 2006, Marsic et al. 2006, Grundfelt 2010).

The concept developed in the Pass project included disposal of 50 centimetre diameter canisters containing four BWR or one PWR elements. The disposal holes were assumed to have an 80-centimetre diameter and the canisters were assumed to be emplaced in the hole at between two and four kilometres depth. A weak point of the Pass project concept is the wide borehole, which is beyond the experience of the drilling industry. In more recent studies (Beswick 2008, Odén 2013), a consensus has developed that it would be feasible to drill 5 km deep holes with a diameter of 0.5 metre or less in hard rock, although also this would require additional technology development.

Following the cessation of the US Yucca Mountain programme, Sandia National Laboratories, SNL, has engaged into studies of deep borehole disposal. A concept based on disposal of strings of 40 canisters (~200 metres long) between 3 and 5 kilometres depth (Arnold et al. 2011). In the design preferred by SNL, the borehole diameter is assumed to be 17” (about 43 cm). This limits the size of the canister so that it can host only one fuel element without consolidation of the fuel. In a previous report (Brady et al. 2009) an alternative design including 17½” (44.5 cm) diameter holes was presented. Such a hole would allow a canister that could hold two BWR or one PWR elements. Hence, following the results of these later analyses, SKB has decided to base this study on the borehole diameter 44.5 cm to and apply the borehole construction and operation procedures described by Arnold et al. (2011). The design and procedure is described by Odén (2013).

1.2 Summary of previous geoscientific findings of relevance to disposal in deep boreholes

Juhlin et al. (1998) presented a geoscientific appraisal of the conditions at great depth. The findings of this study were summarised in a conceptual model for the groundwater circulation to a depth of about 5,000 metres, see Figure 1-1. This model stipulates that circulation of saline groundwater beneath a halocline are in essence stagnant. In topographically flat areas the halocline is located at a depth of about 1 kilometre whereas the fresh water circulation goes much deeper in areas with a steeper topographic relief.

Smellie (2004) presented an update of geoscientific information of relevance to disposal of spent nuclear fuel in deep boreholes in Sweden that had become available since the study by Juhlin et al. (1998). The focus of Smellie's study was on crystalline rocks relevant to the disposal of spent nuclear fuel in deep boreholes according to the concept that was developed in the PASS study (SKB 1992). The deep drilling programmes providing most of the relevant data of interest to SKB were:

- Russian boreholes
  - SG-3 (12,262 m, in Zapolyarny at the Kola peninsula)
  - SG-4 (~5,400 m, Tagil Volcanic Arc, Middle Urals)
  - Vorotilovo (5,374 m, in the East European Platform)
- German boreholes
  - The KTB site (German Continental Deep Drilling Programme at the western margin of the Bohemian Massif)
  - KTBV (4,000 m, pilot borehole)
  - KTBH (9,101 m)
- Other national programmes focused on Geothermal Energy or Hot Dry Rock (HDR) Technology deep in crystalline rocks.

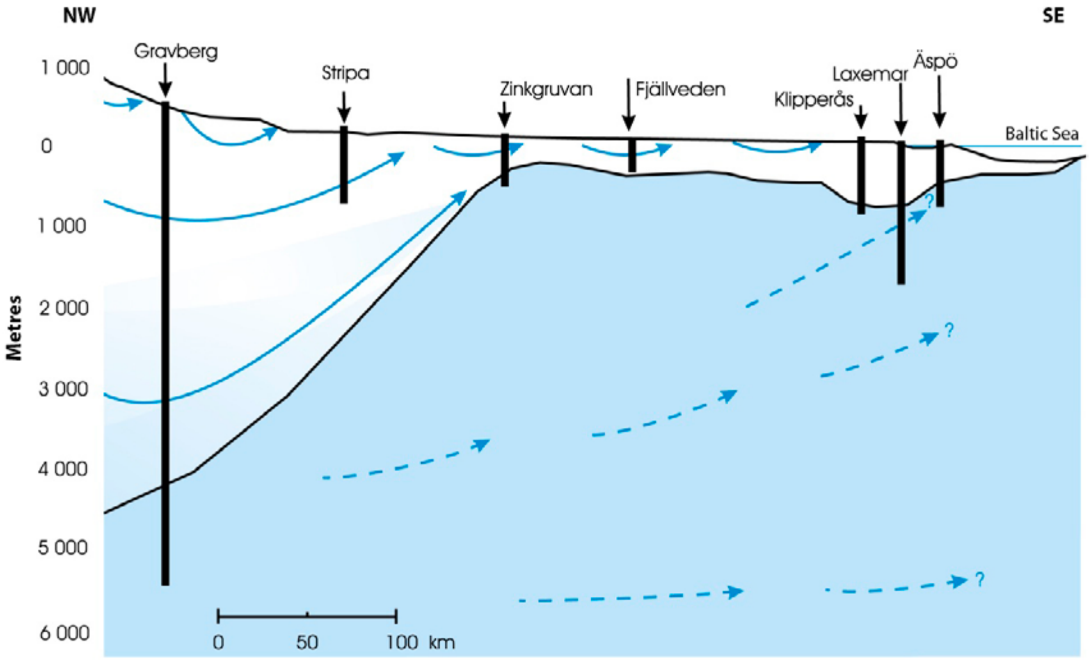

Figure 1-1. *Groundwater circulation and salinity variations along north-west – south-east profile through Sweden. Boreholes along the profile have been indicated in the figure. Modified after Juhlin et al. (1998).*

Figure 1-2. *Boreholes providing most of the data in the previous review by Smellie (2004).*

The main conclusions from Smellie (2004) with respect to disposal in deep boreholes were:

Thermal conditions

- Since granitic rock are usually less heat conductive than a mafic rock varieties, they may be considered more problematic in terms of dissipation of the residual heat generated by the deposited spent fuel.
- Fractures tend to increase the thermal conductivity; however due to the rock stress the frequency of fractures decreases with depth so that a decrease in thermal conductivity with depth is to be expected.
- Thermal conductivity profiles were determined in the Kola SG-3 and Vorotilovo boreholes. Both holes show obvious thermophysical boundaries corresponding to lithological limits, indicating the sensitivity of thermal conductivity to changes in mineral composition, structural features etc.
- The SG-3 borehole shows that the heat flow density is consistent with the thermal conductivity where a series of vertical variations relate to movement of fluids in the rock, sometimes resulting in non-stationary fields.
- 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.
- Due to geographical and geological similarities, the Kola SG-3 borehole is considered to be a good approximation to expected temperature conditions for Swedish repositories. At 4,000 m depth, the temperature was recorded to approximately 60°C at 4,000 m depth, 95°C at 6,000 m depth and 130°C at 8,000 m depth, i.e. a geothermal gradient of about 15ºC/km. The linear temperature behaviour seen in the Kola borehole does not apply to the German KTB boreholes where temperatures at 4,000 m depth lie well above the values calculated from superficial temperature gradients.

Hydraulic conditions

- The rock permeability[1] is expected to be in the order of (1 to 3) x 10^{-13} m^2 over a 1–2 km depth zone, 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.
- In areas with flat 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 ancient and no recent meteoric water input is observed.
- In areas with a more expressed topographic relief (e.g. the Gravberg-1 site close to the Swedish high lands 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 down to at least 9 km. However, most 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.
- Evidence shows that active saline groundwater circulation does exist but is restricted to intermittently occurring hydraulically conductive fracture zones. Nevertheless, at some locations (notably the KTB site) it was concluded that even in a high salinity environment relatively rapid solute transport in fracture systems is possible.

Hydrogeochemical conditions

- At repository depths long-term hydrochemical stability appears to be assured where hydraulic conditions are favourable (i.e. flat 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. Moreover, fracture mineral chemistry and fluid inclusion studies support that the saline water is long-term stable. As a consequence, solute transport through the bedrock will be diffusion dominated provided that major hydraulically conductive fracture zones are avoided.

Bacteriological activity

- Microbial activity at great depths and high temperatures may have effects on borehole casing and canister materials used in deep disposal concepts.
- Existence of bacteria has been noted down to a depth of 1,500 m. However, the temperature seems to be a more important limiting factor for the presence of living organisms at depth. In the KTBV borehole, hyperthermophiles were not found in fluid samples at 4,000 m depth in a temperature of 118°C. The highest culturing temperature for hyperthermophiles has not exceeded 113°C. In the Gravberg-1 borehole, thermophilic bacteria were found below 5,200 m at a temperature of 65–75°C.
- 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, i.e. the temperature above which life micro organisms cannot be sustained, will be exceeded at disposal depths. However, provided that 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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[1] Hydraulic conductivity K (m/s) is often used instead of permeability k (m^2): $K= k\cdot(\rho\cdot g/\mu)$ where ρ is the density of the fluid, g is the acceleration of gravity and μ is the dynamic viscosity of the fluid.

2 Data sources

The objective of the current study is to provide an update the geoscientific data from formations that could be of relevance for disposal of spent nuclear fuel in up to five kilometres deep boreholes in crystalline rock in Sweden. An inventory of deep boreholes in Europe that have been reported after the previous update of geoscientific information (Smellie 2004) is summarised in Table 2-1. Boreholes for exploration of exploitation of oil or gas reservoirs have been excluded as they, with few exceptions, are drilled in sedimentary settings. Also, geoscientific data from exploration boreholes are very rarely are publicly available.

One of the identified boreholes was drilled for research purposes while the other have been drilled for geothermal exploration or exploitation purposes. After having reviewed the documentation of the boreholes, it was concluded that only three of the geothermal holes have been drilled into crystalline rock. The boreholes included in the study have been highlighted with colour in Table 2-1. The locations of the drilling sites are shown in Figure 2-1. Also in the figure the projects of relevance to disposal of spent nuclear fuel in deep boreholes in Sweden have been marked with a separate colour.

Table 2-1. Inventory of European deep boreholes (excluding holes for oil and gas exploration or exploitation) reported after the publication of Smellie (2004). The highlighted projects have been judged to be of greater relevance to disposal in deep boreholes in Sweden as at least parts of the boreholes are located in crystalline rock.

No	Location	Name	Company	Year	Type	Geology	Length/ Depth (m)
1	Outokumpu, Finland	Outokumpu Deep Drilling Projekt	Geological Survey of Finland (GTK)	2003–2010	Scientific research	Meta-sedimentary/ Crystalline	2,516
2	Lund, Sweden	Lund Djupgeotermi (DGE#1)*	Lunds Energi AB and LTH	2001–2007	Geothermal	Sedimentary/ Crystalline	3,701
3	Soultz sous Forêts, France	Soultz HDR project (GPK3 & GPK4). Rhine Graben	BRGM	2005	Geothermal	Sedimentary/ Crystalline	5,250
4	Basel, Switzerland	Basel-1, Rhine Graben	Geothermal Explorers Ltd	2004–2007	Geothermal	Sedimentary/ Crystalline	5,009
5	Kirchweidach, Germany	Kirchweidach 1			Geothermal	Sedimentary	4,937
6	Kirchweidach, Germany	Kirchweidach 2			Geothermal	Sedimentary	5,133
7	Maurerstetten, Germany	Maurerstetten			Geothermal	Sedimentary	4,545
8	Dürrnhaar, Germany	Dürrnhaar 1			Geothermal	Sedimentary	4,393
9	Dürrnhaar, Germany	Dürrnhaar 2			Geothermal	Sedimentary	4,530
10	Kirchstockach, Germany	Kirchstockach 1			Geothermal	Sedimentary	4,214
11	Kirchstockach, Germany	Kirchstockach 2			Geothermal	Sedimentary	4,452
12	Hanover, Germany	Hanover			Geothermal	Sedimentary	3,902

* A second hole, DGE#2, was drilled to a depth of 1,927 m mainly in sedimentary rock.

***Figure 2-1.** Locations of the drilling projects analysed. The projects marked with green markers were judged to be of relevance to disposal of spent nuclear fuel in Sweden whereas the projects marked with red markers were located in geological settings that were judged to be of no relevance in this context.*

3 New and supporting data

3.1 Outokumpu Deep Drilling Project

The main aims of the Outokumpu Deep Drilling Project were set as:

1. understanding the deep structure of the Outokumpu ore belt;
2. understanding the composition and origin of the saline fluids and gases in the bedrock and studying the deep biosphere;
3. investigating the vertical variation in different geological and geophysical parameters and correlating various data sets;
4. using the Outokumpu hole after drilling as a deep geolaboratory.

The deep drill hole R2500 was drilled in 2004–2005 by the Outokumpu Deep Drilling Project of the Geological Survey of Finland (GTK), within an international framework partly supported by the International Continental Scientific Drilling Program (ICDP). The research was conducted during 2003–2010 (Kukkonen 2011).

The Outokumpu region is located in the Fennoscandian Shield in eastern Finland in a classical ore province with massive Cu-Co-Zn sulphide deposits within the Palaeoproterozoic Karelian schist belt close to the boundary between the Neoarchaean craton in the east and the Palaeoproterozoic Svecofennian island arc complex in the west.

The drill hole is located south-east of the town Outokumpu in the metasedimentary allochthonous upper part of the Kalevian unit in the upper part of the Karelian schist. Figure 3-1 shows a geological map of the area with the location of the drill hole indicated (Kukkonen et al. 2011).

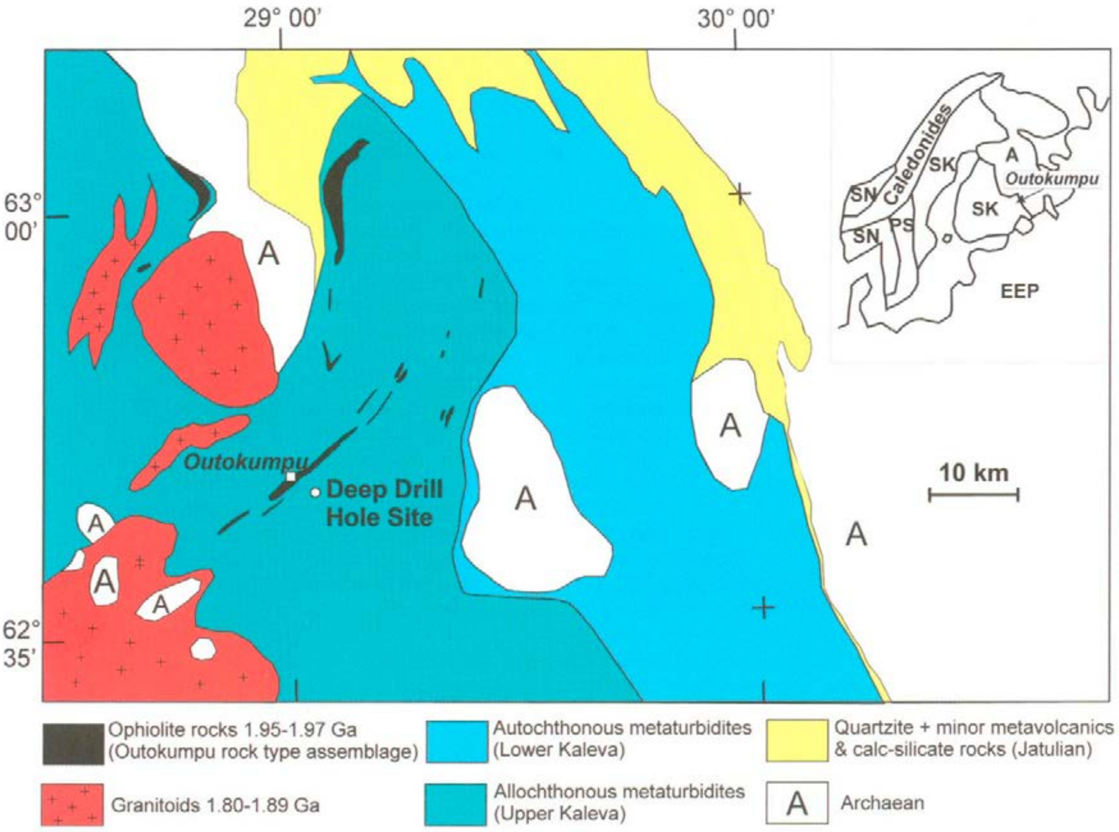


Figure 3-1. Geological map of the Outokumpu area (Kukkonen et al. 2011).

The length of the sub-vertical hole is 2,516 m, with the hole bottom at a depth of 2,497 m, and deviates only 9° from a vertical direction with a north to north-west strike. Continuous coring was carried out during the drilling operation. In addition, samples of drill cuttings (~2 kg) were collected at intervals of 5 m. The final core recovery was 79%. A Ø324 mm casing extends down to 39 m of the hole, through Quarternary soft sediments. Beneath the casing, the open hole is ca. Ø220 mm and provides direct access to the crystalline bedrock in situ. The drill core diameter is mainly 100 mm and only occasionally 60 or 80 mm. The hole has been kept open for national and international use as a deep laboratory facility for different short and long-period experiments to be carried out in the borehole (Västi 2011).

Figure 3-2 shows a simplified lithological profile along the borehole. Figure 3-3 shows a summary of depth-related data obtained from the hole (from Ahonen et al. 2011). Specificities of these and other data are discussed in the following sections.

3.1.1 Hydraulic conditions

The hydraulic permeability (conductivity) was measured every 500 m of drilling. However, only the two uppermost measured sections were flowing and results are therefore only available for these two sections. For the section at ca. 500 m depth, a permeability of $6.8 \cdot 10^{-13}$ m^2 (a conductivity of $7.5 \cdot 10^{-6}$ m/s) was estimated and for the section at 1,000 m depth, a permeability of $4.8 \cdot 10^{-14}$ m^2 (a conductivity of $5.3 \cdot 10^{-7}$ m/s) was estimated. In the deeper sections studied, the permeabilities were significantly lower and they were considered as practically impermeable. This suggests that fractures become more efficiently closed by lithostatic pressure with increasing depth (Ahonen et al. 2011). It should be noted that the two stated permeability values are relatively high compared to values often found in crystalline bedrock. The data were measured using drill-stem tests that may have had a rather high detection limit. Post-drilling inflow of formation water to the borehole indicates the presence of conductive fractures also at depth.

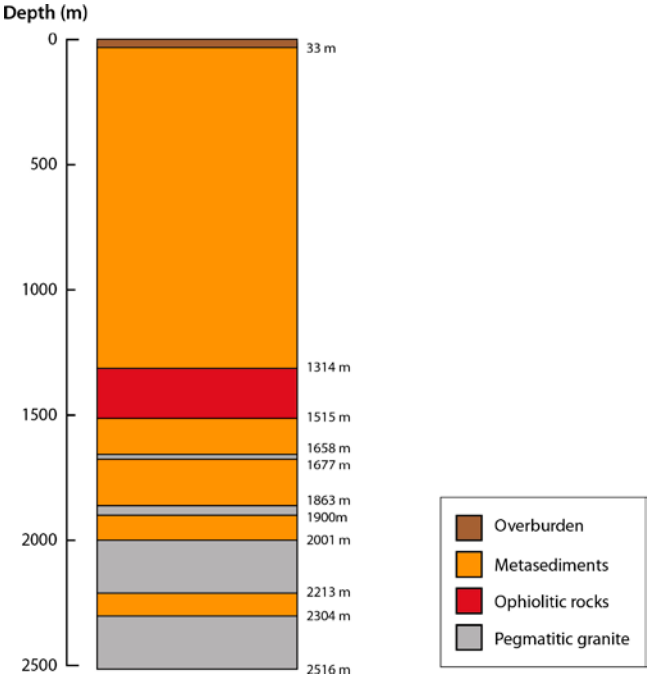


***Figure 3-2.** Simplified lithological profile of the borehole (after Kietäväinen et al. 2013).*

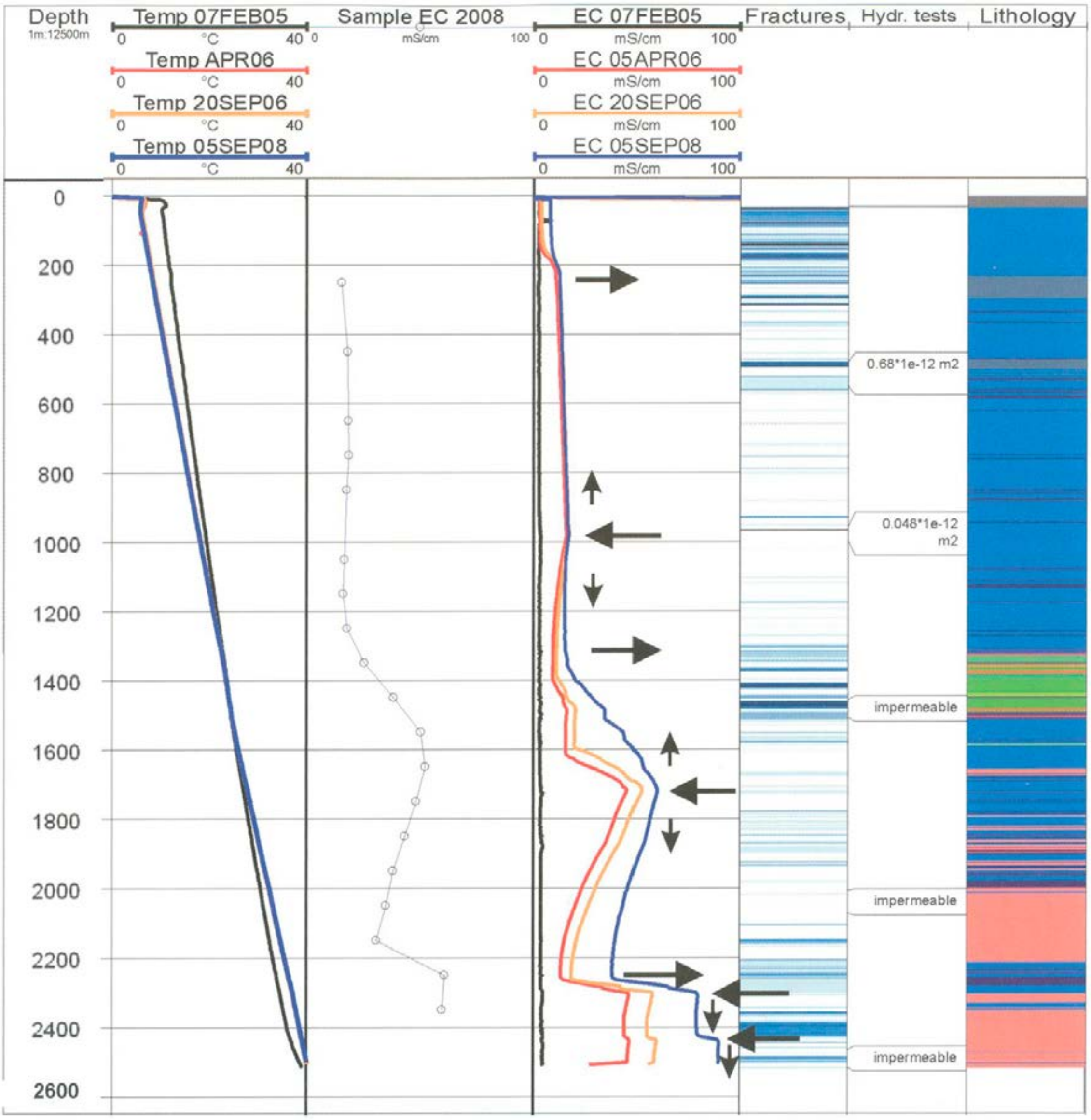


Figure 3-3. *Temperature and fluid electrical conductivity logs in the Outokumpu Deep drill hole 2005–2008."Sample conductivity" refers to results of tube sampling of drill hole water in 2008. "Fractures" refers to interpretation of sonic, galvanic and caliper logs. "Lithology" shows the rock types (blue: metasediments; green and orange: ophiolite-derived serpentinite and skarn rocks; pink: pegmatitic granite). Arrows pointing to the left indicate interpreted points of saline formation water inflow to the hole and arrows to the right outflow from the hole. Vertical arrows indicate interpreted flow directions in the hole. (Ahonen et al. 2011).*

Based on the results from hydraulic tests, geophysical measurements and observations from the drill core, eight hydraulically conductive main fracture zones are interpreted to exist along the length of the drill hole. Formation waters from the surroundings discharge from fractures at depths of 500 m, 967 m, 1,700 m, 2,300 m and 2,400 m. Recharge from the hole into the surrounding bedrock aquifers is interpreted to occur at 220 m, 1,300 m and 2,250 m depth. The stable isotope composition of the inflowing water suggests that the water bodies at different levels are isolated in fracture zones with minimal hydraulic connections. (Ahonen et al. 2011).

The water table in the deep drill hole has been monitored as well as water levels in a shallow (17 m deep) hole in the Quaternary overburden in Outokumpu. The results show that the water in the deep hole has no hydraulic connection with the shallow sediments.

3.1.2 Geothermal conditions

High resolution geothermal studies, including five down-hole temperature loggings and thermal conductivity measurements at one meter intervals of the Outokumpu drill hole, has been reported. The temperature gradient, thermal conductivity and heat flow density results yield an exceptionally detailed geothermal data set and indicate significant vertical variation in the gradient and heat flow density (Kukkonen et al. 2011).

Temperature gradient

The temperature gradient shows a distinct vertical increase from about 13–14°C/km at 50 m– 1.3 km (in the upper mica schist unit), lower but more variable values of 10–13°C/km at 1.3–1.5 km (in the ophiolite-derived rocks), and about 16°C/km in the lower mica schist unit and pegmatitic granite at 1.5–2.2 km. In the lowermost part of the hole at 2.2–2.5 km, the temperature gradient displays lower but variable values in the range of 13–16°C/km (Kukkonen et al. 2011). These gradient values are consistent with what is generally considered to be representative values for the Fennoscandian shield (Juhlin et al. 1998, Ahlbom et al. 1995).

Thermal conductivity

The measured thermal conductivity is very stable in the mica schist and pegmatitic granite. In the mica schist the average thermal conductivity is 2.5 W/m, K. The foliated rock is thermally anisotropic, but the (sub)horizontal orientation of foliation in the drilled section results in relatively low conductivity values, as the conductivity is measured in a direction perpendicular to schistosity and foliation. In the pegmatitic granite, the average conductivity is 3 W/m, K (Kukkonen et al. 2011).

Heat flow density

The heat flow density was determined to increase from about 28–32 mW/m^2 in the uppermost 1,000 m to 40–45 mW/m^2 at depths beneath 1,500 m. The results suggest that the vertical variation in heat flow can mostly be attributed to a palaeoclimatic effect due to ground surface temperature (GST) variations during the last 100,000 years (Kukkonen et al. 2011).

The topographic hydraulic heads and hydraulic conductivity of the crystalline rocks at Outokumpu are low, which suggests that advective heat transfer in the formation is not significant. Heat transfer in the Outokumpu section is predominantly conductive, and no relevant advective heat transfer effects due to groundwater flow could be observed (Kukkonen et al. 2011).

3.1.3 Hydrogeochemical conditions

Saline gas-bearing fluids are present in the fracture zones of the bedrock. A general trend of increasing salinity towards the bottom was observed, although the changes are abrupt rather than gradual. Total dissolved solids (TDS) of up to 64 g/L were measured at 2,400 m depth in the borehole. Down 1,400 m depth, the sampled TDS values were between 11 and 13 g/L. From 1,500 m depth, the TDS value increased from 15 g/L to ca. 50 g/L at 2,000 m depth. The sampled water, at 967 m depth in particular, also contained significant amounts of gas, mainly CH_4, N_2, H_2 and He.

TDS increases from about 12 g/L in the uppermost 1,000 m to about 50 g/L at the bottom of the borehole. Based on the molar Ca:Na ratio, processes affecting salinity differ with depth: the Ca:Na ratio is 0.8 in water of the uppermost 1,200 m and 1.7 in the depth range 1,500–2,200 m, while the deepest, most saline samples are most clearly Ca-dominated, having a Ca:Na ratio of 2.4. The molar ratio of bromide vs. chloride (Br:Cl = 0.0028) is uniform throughout the uppermost 1,200 m of the borehole, also supporting a common source, whereas variation was observed between water samples discharging from deeper fractures (0.025 < Br:Cl < 0.035). A striking feature of the deepest water is the high lithium concentration, showing a ten-fold increase (up 15–17 mg/L) below the depth of 2,200 m.

Geochemical and isotopic (δ^2H, δ^{18}O, ^{87}Sr/^{86}Sr) composition of deep saline waters were sampled at the Outokumpu deep drill hole. The δ^2H varies from −90‰ to −56‰ (VSMOW) and δ^{18}O from −13.5‰ to −10.4‰ (VSMOW), plotting clearly above the Global and Local Meteoric Water Lines on a δ^2H vs. δ^{18}O diagram, see Figure 3-4. The ^{87}Sr/^{86}Sr ratios range between 0.72423 and 0.73668 (Kietäväinen et al. 2013).

Five different water types were identified along the borehole section. All the samples were distinct from fresh groundwater in the area, and had isotopic compositions typical of shield brines. In the uppermost 300 m, the first water type, which most closely resembles meteoric waters, is found. From 300 m to 1,300 m depth, a second water type with relatively ^{2}H- and ^{18}O-poor, CH_4-rich water, dominated the borehole profile. Two major fracture systems are present within this depth range. Between 1,000 m and 1,700 m, a third distinctive layer of Mg-rich water, affected by the rocks of the Outokumpu assemblage, is found. The fourth, relatively ^{2}H- and ^{18}O-rich, water type is present below 1,700 m. The fifth and most saline, although not the most ^{2}H- and ^{18}O-rich, water type with abundant H_2 and He was sampled below 2,300 m (Kietäväinen et al. 2013).

The most likely mechanism to have caused the variation of the δ^2H and δ^{18}O values of the five different water types is hydration of silicate minerals by ancient groundwater recharged under warmer climatic conditions. The formation of zeolites is another possible contribution to the increase of salinity at deeper levels. Simple two component mixing between an end-member brine with high δ^2H and δ^{18}O and meteoric water cannot explain the isotopic evolution of the Outokumpu deep drill hole waters. In addition, Sr isotopes indicate strong water–rock interaction in the deeper, more saline waters. In accordance, long residence times on the order of tens of millions of years for the deeper waters are likely. Isotopic results do not indicate any contribution of glacial melt waters (Kietäväinen et al. 2013).

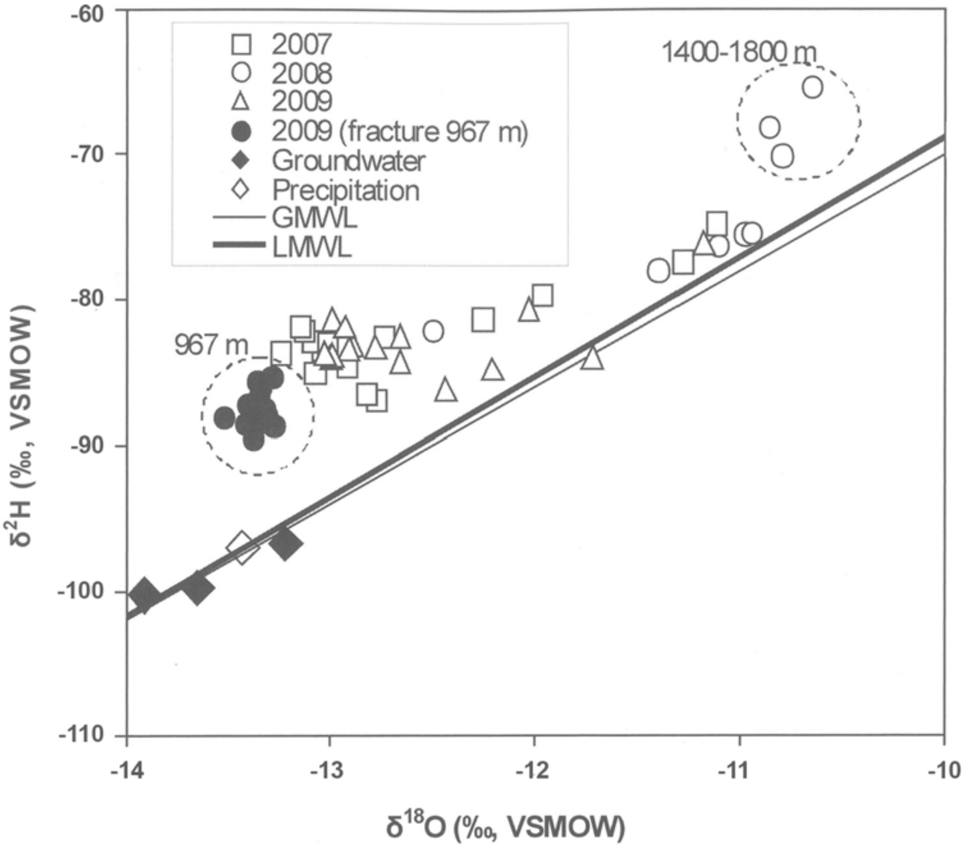


Figure 3-4. *δ^2H and δ^{18}O analyses of drill hole water from tube sampling of the Outokumpu hole in 2007–2009 and in pumped water from a fracture zone at 967 m depth. GMWL=global meteoric water are from Craig (1961). LMWL=local meteoric water from Kuopio in eastern Finland, groundwater (solid diamonds) and precipitation values are for Kuopio and Lieksa (open diamonds)are from Kortelainen (2007). Circled points represent different compositions of water discharging from fracture zones at 967 and 1,715 m and mixing with borehole water (Ahonen at al. 2011).*

Two of the in situ samples, from the test sections 1,000 m and 1,500 m, contained a gas phase providing information on the undisturbed fracture fluid conditions. The predominant gases in both gas samples were methane and nitrogen. Alkanes were present in successively decreasing relative proportions in both samples: methane 100% > ethane 1.3% > propane 0.04%. Interestingly, alkenes (ethene and propene) were detected in the deeper sample, whereas the concentrations of these unsaturated gases were below the detection limit in the 1,000 m sample. The gas phase of the sample from 1,500 m was distinctly dominated by nitrogen (86% of total gas volume). Based on the low oxygen content, air contamination is unlikely, and the result may therefore reflect the true formation gas composition. The absence of the tracer compound in the sample supports its deep bedrock origin

Together with the hydraulic test results, the differences in EC, stable isotopes as well as the cation composition of the water indicate distinct water bodies isolated in fracture zones with minimal hydraulic connections (Ahonen et al. 2011).

Micro thermometrical measurements were performed on five quartz samples that were taken from mica gneisses from the depths of 145.30 m, 620.80 m, 1,212.55 m, 1,561.10 m and 2,503.30 m. The purpose was to examine primary CO_2 inclusions but most inclusions turned out to be secondary. The lack of primary fluid inclusions is probably a consequence of quartz decomposition and recrystallisation during uplift, releasing those fluid inclusions that would have been entrapped during the high pressure metamorphism (Hölttä and Karttunen 2011).

Fluid inclusions may affect groundwater composition due to fluid diffusion via micro cracks. Samples of fluid inclusions in quartz veins in the Outokumpu deep drill hole were analysed and the data on measured primary fluid inclusions reflect a complicated pattern. The distribution of salt species (NaCl and $CaCl_2$) and associated salinity of the fluid shows no correlation with depth. The strong variability of the fluid characteristics of primary fluid inclusions shows the occurrence of more than one fluid pulse during the formation of the metamorphic quartz veins. Based on their composition, fluid inclusions could have influenced groundwater chemistry. In addition to an aqueous phase, fluid inclusions also contain gaseous phases such as CO_2 and CH_4.

While Br/Cl–I/Cl characteristics indicate that Outokumpu groundwater could be derived from a mixing of seawater and fluid inclusions water, the relatively high Na/Br ratios within fluid inclusions as well as the lack of a transgressive stage in the younger geological history in the Outokumpu region argue against simple mixing. In addition, other studies also preclude a seawater input in the region of Outokumpu.

In summary, the stable isotope composition, notably δ^2H and $\delta^{18}O$, of the deep saline fluids indicate that these waters have been isolated from modern meteoric influences. The waters are significantly different from the isotopic composition of meteoric waters, such as the local precipitation and modern groundwater. These are also typical characteristics of waters affected by long-term geological processes in crystalline bedrock. Based on the δ^2H and $\delta^{18}O$ values, no admixture of deep water and local groundwater can be detected from the water profile of the borehole. Therefore, the stable isotopes suggest water bodies with different compositions that are isolated in fracture zones with minimal hydraulic connections. This is also evidenced by the absence of tritium.

The variation in magnesium concentrations in the water samples clearly reflects the effect of water-rock interaction. Notably the Mg level in water samples as well as in the drilling fluid is at its highest near the Mg-rich Outokumpu formation rocks.

At Outokumpu, the isotopic composition of fluid inclusions in the deep drill hole differs significantly from the one measured in the groundwater. Thus, fluid inclusions, which can be characterised as metamorphic water, are not assumed to have a significant effect on the groundwater composition. Rather, groundwater appears to be derived from meteoric water, the composition of which changed due to fluid–rock interaction. Furthermore, the elevated Br/Cl values point to brines generated during long-term water–rock interaction. This is also supported by earlier studies where it was stated that the Sr concentration and Sr isotope characteristics can only be explained by the breakdown of minerals such as feldspars.

Despite the possibility of fluid inclusions losing their content by diffusion or microcracking, the results from the Outokumpu deep drilling project do not support that fluid inclusions of rocks exposed in the borehole have influenced the salinity of the Outokumpu groundwater (Piribauer et al. 2011).

3.1.4 Bacteriological activity

Microbiological sampling of the deep biosphere in the Outokumpu deep drill hole revealed the presence of microbial communities in the saline fluids sampled from the open borehole and intersected fracture zones in the crystalline bedrock. According to the microbiological analyses, the microbial cell density varies from 10^5 cells/ml at the surface to 10^3 cells/ml at 2,350 m depth.

Although microbial cell densities decrease downwards in the borehole, microbial diversity was not directly connected to the decrease in the cell number. Instead, a higher number of bacterial classes are observed at 1,500 m depth than at 100 m or 1,000 m.

The composition of microbial communities in the borehole was found to vary with sampling depth, and the changes appear to be connected to both geological and geochemical factors as well as to fracture zones in the bedrock and gas composition.

Microorganisms were detected in the sampled fluids at all depth levels in the hole. The microorganisms represent sulphate reducing bacteria and methanogenic archaea, but in addition there are numerous previously uncharacterised species (Itävaara et al. 2011)

Changes in bacterial communities with depth correlate with the different water types and the results imply that distinct ecosystems may actually have remained separate for long periods of time at different depths (Kietäväinen et al. 2013).

3.1.5 Rock mechanical properties

The uppermost 2,000 m of the drill hole consists mainly of gently dipping metasedimentary rocks, i.e. monotonous mica schist (fine- to medium-grained with a typical grain size of <0.6 mm) with minor biotite gneiss, chloride-sericite schist, black schist and hornblende-epidote schist intercalations. Within the interval of 1,300–1,500 m the hole encloses a previously unknown occurrence of ophiolite-derived altered ultramafic rocks (Outokumpu assemblage). From ca. 1,650 m downwards mica schist is intruded by pegmatitic granitoids (classified as tonalites and granodiorites), which in turn dominate from ca. 2,000 m downwards. The abundance of pegmatitic granite was not predicted before drilling. The thickness of the intrusive pegmatite bodies or dykes varies from ca. 200 m to a few cm. The pegmatitic granitoids are massive and mostly very coarse-grained, typically lacking orientation. Below 2,000 m, a disking effect is seen in which pegmatites fracture into plate-like disks 1 to 5 cm thick, as a consequence of strong confining pressure. The Archaean basement was not encountered in the deep hole (Västi 2011).

The porosity in mica schist increases with depth from ca. 0.2% to ca. 0.7%. The pegmatitic granitoids show the same general trend with depth. The increase in porosity with depth can partly be attributed to drilling-induced stress-relaxation microfracturing. However, in the case of stress-relaxation induced porosity, the densities should also be affected, but contrary to this the drill core bulk densities do not change, whereas the grain density tends to increase with depth. This could indicate a mineralogical change in the mica schist.

The overall variation in densities in the Outokumpu drill hole is mainly related to variation in the rock types and their mineral concentration. Serpentinites and pegmatitic granitoids have the lowest densities with a value of around 2,600 kg/m^3 while different schists have densities of 2,700–2,800 kg/m^3 (Airo et al. 2011).

3.2 Lund – DGE#1 and DGE#2

In the beginning of 2000 the Department of Engineering Geology at Lunds Institute of Technology initiated a project to investigate the tectonised basement within the Tornquist deformation zone close to the city of Lund. The project was a co-operation between Lunds Energi AB and the Department of Engineering Geology and was executed from the second quarter of 2001 to the end of 2003. The aim was to extract hot water from deep-seated fractures in the basement created by tectonic activities in the deformation zone. An estimation was done that temperatures around 110–125°C could be at hand at a depth of around 3,500 m. This was based on the results from years of studying of the temperature gradient in the region. Another task within the drilling project was to investigate different drilling methods and their applicability in basement rock drilling.

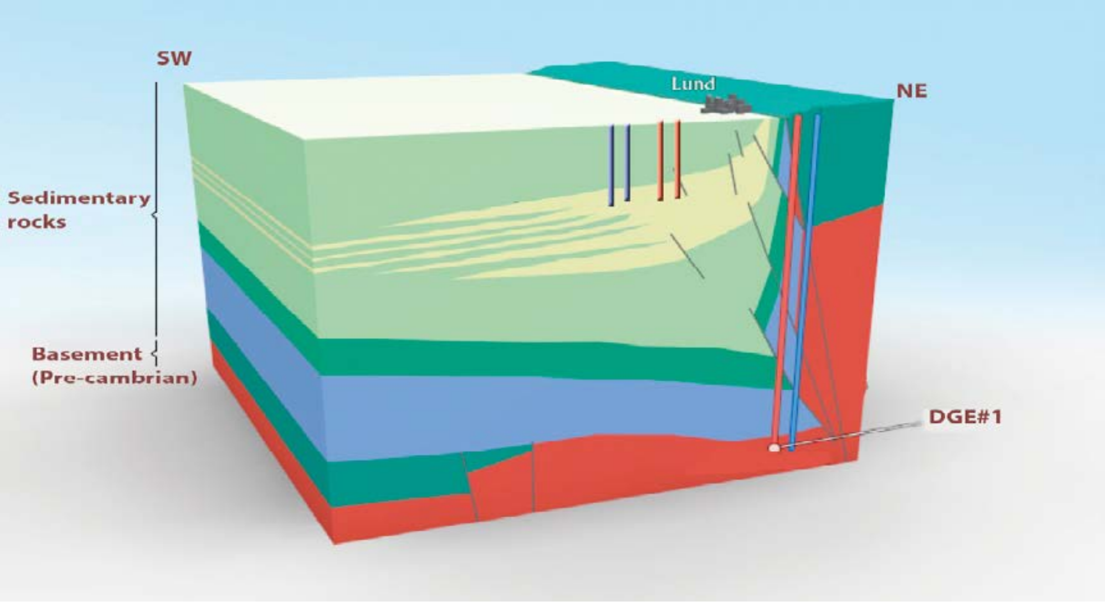
The sites for the exploration wells DGE#1 and DGE#2 are located within the fault zone running along the Romele horst ridge in Stora Råby south-east of Lund in southern Sweden. The distance between the boreholes is 1,300 m. Figures 3-5 and 3-6 show a perspective view of the lithology of the site and the lithological sequence of borehole DGE #1 respectively.

The investigated area is a part of the Tornquist zone (also called Tornquist-Teisseyre zone) that is a major tectonic deformation zone stretching from the North Sea into Poland continuing south-east to the Black Sea. The Tornquist zone is also a part of the Fennoscandian border zone, which is the border zone between the Baltic shield and the Danish-Polish embayment.

This border zone is of great importance when studying the geology of Scania (Skåne), the southernmost part of Sweden. The north-east part of the zone, the Baltic shield, consists of basement rocks and the south-west part of the zone, the Danish-Polish embayment, consists of sedimentary rocks resting on basement rocks. Along the zone there are a lot of block faults including the Scanian horst ridges, which stretch along this zone in a north-west to south-east trend. The faulting along the Romele horst ridge is both normal and reverse faulting. The vertical displacement in this area can be as much as 1,500–2,000 m.

The drilling operation of borehole DGE#1 started in October 2002 and became the second deepest drilling project in Sweden. The total depth of the hole is 3,701.8 m and it is cased down to 3,200 m using a stepwise decreasing casing diameter downwards along the borehole. The drilling was performed in both sedimentary rock and in the crystalline basement.

The drilling and initial testing was completed on March 19, 2003. Flow tests and injection tests were carried out both in the crystalline basement and in the sandstones in the sedimentary deposits. A decision to drill a second well was made after evaluating the results from the flow- and injection tests of the sedimentary deposits.



Figur 3-5. Schematic cross section through the bedrocks below Lund. The boreholes to the left show the low temperature system, which was drilled in the 1980s (550-750 m depth) (Bjelm and Rosberg 2006).

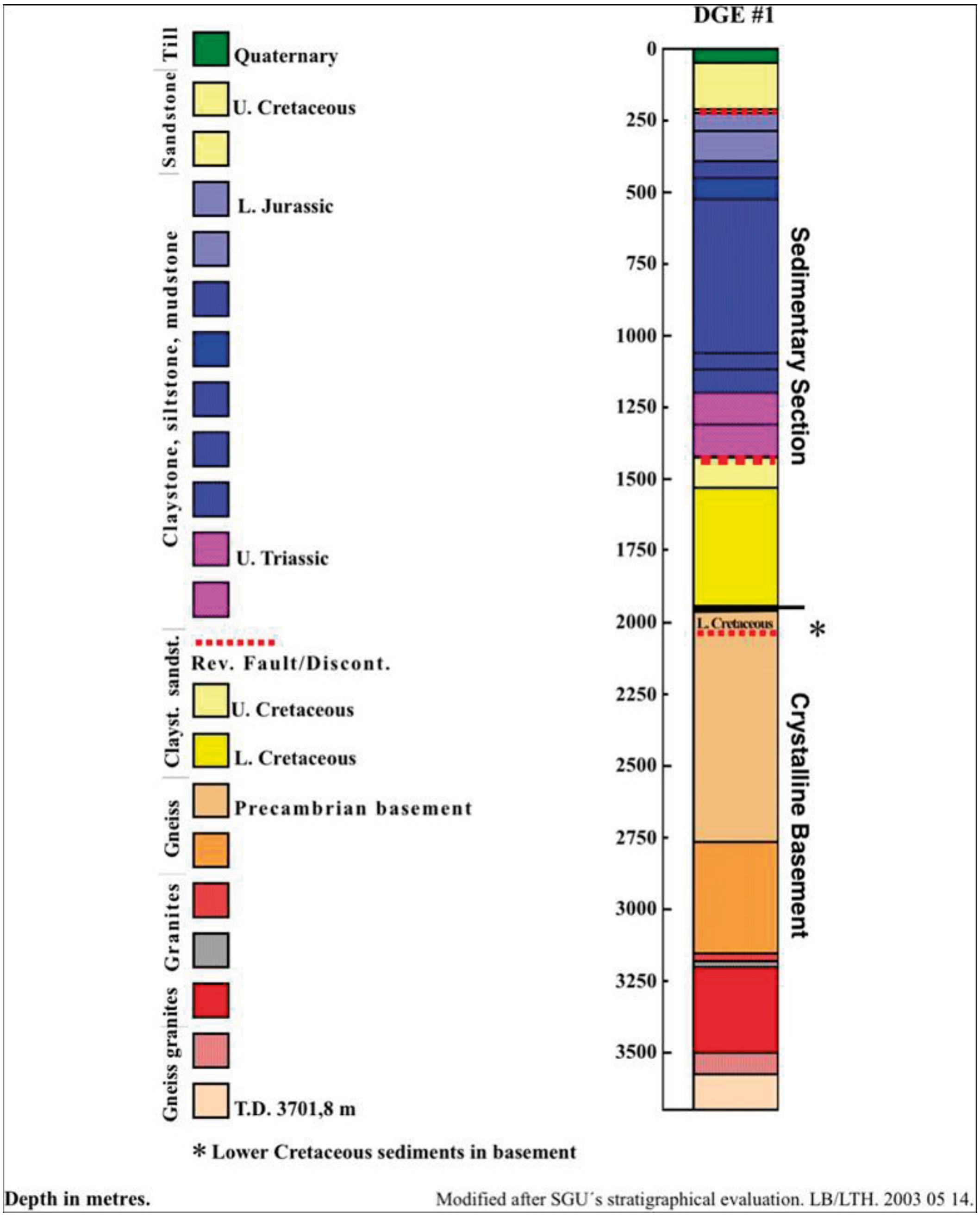


Figure 3-6. *Geological profile showing that the bedrock from about 2,000 m consists of gneiss, granite and gneiss granites (Bjelm 2007).*

The second well, DGE#2, was drilled during the summer 2004 mainly in sedimentary rock to a total depth of 1,927 m. The drilling was terminated after penetrating the basement. This well was thought to be the production well for geothermal heating and the first well DGE#1 should be the injection well. Different well completions were used for the two wells. DGE#1 is a perforated well and DGE#2 is a gravel packed screen completed well. The well testing included pumping tests, recovery test and step drawdown tests in both of the wells. Injection tests and fall off tests were onlyperformed in DGE#1.

3.2.1 Hydraulic conditions

Flow testing of DGE#1 was conducted during two different periods. The first was in March 2003 and the second was between September and December 2003. The first test was carried out to evaluate the hydraulic properties of the basement rock formation and the second was to evaluate the hydraulic properties in the basement rock and in the sedimentary rock formation.

An estimation of the transmissivity from injection and fall off tests of the open hole section in DGE#1 in the crystalline basement gave values of $4.7 \cdot 10^{-7}$ m^2/s and $5.2 \cdot 10^{-7}$ m^2/s. Using the average transmissivity of $5.0 \cdot 10^{-7}$ m^2/s and a length of the open hole section of 504 m the hydraulic conductivity was estimated to $9.9 \cdot 10^{-10}$ m/s. This is the minimum value of the hydraulic conductivity, because of the assumption that the whole thickness of the open hole is contributing to the flow. More likely is that only parts of the open hole are contributing; if that is the case the value of the hydraulic conductivity will be larger in those parts (Rosberg 2007).

Testing of the Late and Early Cretaceous sandstone in DGE#1 was performed with airlifting followed by a recovery period. The transmissivity has been estimated both from drawdown data during production and from pressure build up data from the recovery. The range of the calculated hydraulic conductivities of these sedimentary rocks is $1.2 \cdot 10^{-5}$ m/s to $1.1 \cdot 10^{-6}$ m/s. The storage coefficient was estimated to $2.4 \cdot 10^{-4}$ and the density of the fluid was around 1,140 kg/m^3 (Rosberg 2006). Note that these values do not carry any significance for the underlying crystalline rock.

3.2.2 Geothermal conditions

Based on data from exploratory oil and gas drillings performed in Scania during the 1970s, the geothermal gradient in the region is estimated to around 30–35°C/km in the area of interest, which is high compared with the most common gradient in Sweden that is around 15–20°C/km (Bjelm and Ottosson 2004).

Temperature gradient

A maximum temperature of 85.1°C was recorded at 3,666 m at the bottom of DGE#1. The water temperature measurement during the testing of the Late and Early Cretaceous sandstone in DGE#1 was disturbed due to injected cold water during the flow test (Rosberg 2006).

The measured temperature profile in DGE#1 was 27°C at 1,000 m depth, 35°C at 1,500 m, 46°C at 2,000 m and 85°C at 3,700 m depth, i.e. the bottom of the hole (Alm and Bjelm 2006). These temperatures represent average temperature gradients of 27°C/km for the upper 1,000m, 16°C/km at 1,000–1,500 m depth 22°C/km at 1,500–200 m depth and 23°C/km at 2,000–3,700 m depth. With the exception of the interval 1,000–1,500 m depth, the estimated thermal gradient are elevated compare to what could be regarded as representative for the Fennoscandian shield (Juhlin et al. 1998, Ahlbom et al. 1995).

3.2.3 Hydrogeochemical conditions

Geothermal waters have different chemical composition compared to e.g. ordinary groundwater. The amount of solutes is often much higher in geothermal waters and there are several reasons for this. Usually, the salinity is high in geothermal waters in sedimentary rocks. In the sandstones present in Scania, salinities of 3–20% can be found. The dominating components are $CaCl_2$ and NaCl. Testing of the Late and Early Cretaceous sandstone (at ca. 1,400–1,900 m depth) in DGE#1 showed a salinity of around 14% (Rosberg 2006).

The geothermal water at the bottom of the DGE#1 was very salty, with more than 20% TDS (Bjelm and Ottosson 2004).

It was expected before the drilling of DGE#1 that the salinity measured in the borehole below 1,000 m would increase by 1% per 100 m and be around 20% at 2,000 m depth, which also was the case. Below 2,000 m, the salinity was expected to decrease down to 10–12% at 3,500 m. It should be noted that the thermal, hydraulic and chemical conditions at these depths were previously unexplored. However, the salinity turned out to be around 20% in the crystalline bedrock as well.

This suggests that saline water coming from the sedimentary formations have infiltrated the fracture system of the crystalline bedrock. This in turn suggests that the Tornquist zone is permeable. There are a number of uncertainties in the water sampling coupled to the test pumping using air-lifting that could have an impact on the measured water chemistry. In addition to the performed water measurements in DGE#1, gases were also analysed. Even if some of the gases found in the borehole were introduced by the air-drilling, the major part originated from gases dissolved in the geothermal water (Bjelm and Ottosson 2004).

3.2.4 Rock mechanical properties

DGE#1 has a total depth of 3,701.8 m and about 1,950 m was drilled in sedimentary rocks (mainly claystone, sandstone, mudstone and siltstone) and the last 1,756 m in basement rocks (mainly gneiss, dolerite, metabasite and granite). The basement was encountered several hundred meters earlier than anticipated. The intrusive rocks are often associated with fracturing probably due to tectonic activities in the deformation zone. The section between 1,985 and 2,050 m also shows that the drilling was performed in a deformation zone, where a repeated layering of basement rock and sedimentary rock was found (Rosberg 2006).

The upper parts of the sedimentary sections of DGE#1 are loose and coarse. The drilling rate of penetration was lower than anticipated in sedimentary rocks. A number of faults were intersected while drilling the sedimentary formations (Bjelm and Ottosson 2004).

The stratigraphy of DGE#2 differs from that in DGE#1 even though the distance between the boreholes is only 1,300 m. Rosberg (2007) concludes that the differences are likely to have been caused by the tectonic processes. However, the sedimentary rocks in DGE#2 are very much the same as for DGE#1, i.e. (mainly claystone, sandstone, mudstone, siltstone and sand) down to 1,924 m. Below this level the rock is crystalline (gneiss) (Rosberg 2007).

3.3 Soultz – GPK1 – GPK4 & EPS1

The Soultz geothermal power production site is located on the western side of the Rhine Graben in Soultz-sous-Forêts, Alsace, France. The Soultz project is part of the European Enhanced Geothermal System (EGS, formerly Hot Dry Rock, HDR) programme and includes four wells. The site was selected for the geothermal project because of its location in the hottest geothermal anomaly of the Upper Rhine Graben.

The two boreholes GPK2 (4,955 m) and GPK4 (4,982 m) are used as production wells and the third central borehole, GPK3 (5,091 m), is used as an injection well. All three wells were stimulated by water injections after drilling. The boreholes were drilled from a single platform in granitic rock during 1999–2004 down to a depth of about 5,000 m. The wells are cased down to approximately 4,500 m depth, and open downwards over a section of about 500 m length. The horizontal distance between the bottoms of the boreholes is about 700 m.

GPK1, which was completed in 1992, is only 3,600 m deep. It was initially used for injection tests and later on for deploying measurement tools. In 1997, EPS-1, an exploration borehole was drilled and fully cored to a depth of 2,227 m. The 800 m length of cores was used to characterise the fracture network properties and the mineralogical composition of the palaeozoic granite (Tischner et al. 2007).

3.3.1 Hydraulic conditions

Data from the EPS 1 well have been interpreted to define number of fracture types in the granite: sub-horizontal joints, steeply dipping filled-joints, and steeply dipping filled-sealed shear-fractures. These fractures are not necessarily hydraulically active. The natural fractures are organised into clusters within the granite defining highly fractured zones. An average fracture density of 3.77 fractures/m (ranging from 0.7 to 9.0 fractures/m) was estimated. The intense-fracture zones correlate with fault zones, and low-fracture intervals correspond to massive unaltered granite. The top of the crystalline basement (at 1,400–2,000 m depth) is more fractured than the lower part (2,000–3,800 m).

The principal fracture orientation (N-S) of the two major fracture sets found in EPS1 is also the orientation of the maximum horizontal stress field. Petrographic studies have shown the presence of organic compounds within the fracture zones in well EPS1. These compounds have probably been transported through the fracture network from overlying sediments. A porosity of less than 1% was estimated for the fresh Soultz granite (Genter et al. 2000).

3.3.2 Geothermal conditions

The geothermal gradient in the uppermost 1,000 m of the sedimentary layers is 105°C/km with a temperature of 120°C at 1,000 m depth. The geothermal gradient then decreases down to 3,000 m and is only 7°C/km between 2,000 and 3,000 m depth. Below 3,000 m, the geothermal gradient increases to an almost constant value of 30°C/km down to 5,000 m where the temperature is about 200°C. The low geothermal gradient between 1,000 and 3,000 m depth is thought to be caused by circulation of groundwater through the fault system. In GPK1 the temperature reached 160°C at 3,600 m depth (Dorbath et al. 2009). With the exception from the section with low conductivity between 2,000 and 3,000 m depth, the measured gradients are significantly higher than the approximately 15 ºC/km what would be expected in the Fennoscandian shield (Juhlin et al. 1998, Ahlbom et al. 1995).

3.3.3 Geology

The geology is similar in GPK3 and GPK4, even if the location of the lithofacies limits does not coincide exactly. The top of the granite is located at a depth of 1,400 m overlain by Cenozoic and Mesozoic sediments. Four different petrographic types were identified in the granitic basement from 1,420 m depth to the borehole bottom in GPK3 and GPK4: (1) standard porphyritic granite, (2) biotite-rich granite, (3) two-mica granite, and (4) altered porphyritic granite related to fractured zones (Dezayes et al. 2005a)

The deep geology of the Soultz site is mainly composed of two main granites with depth. The upper part (from 1,420 to 4,700 m) is referred to the Mega K-Feldspar granite, with a very altered and fractured intermediate section (between about 2,700 and 3,900 m), and the lower part (from 4,700 to 5,000 m, bottom well) corresponds to a two-mica granite. Core studies at Soultz showed that all the natural fractures are filled or partly filled by hydrothermal secondary minerals. The fracture density measured in GPK3 varies between 0.3 and 1.97 fractures/m. In GPK4, the observed fracture densities are higher, with values between 0.23 and 2.86 fractures/m. The fractures are nearly vertical with a dominant orientation close to N-S. There is no relationship between fracture geometry and lithology (Dezayes et al. 2005b).

3.4 Basel – Basel-1

The Basel-1 borehole is located in the city of Basel in north-western Switzerland at the intersection of the southern end of the Upper Rhine Graben and the Jura mountains. The Basel-1 Deep Heat Mining project was initiated in order to develop a geothermal cogeneration plant in Basel. Drilling data, logging and hydraulic tests were interpreted in order to evaluate the geological and hydraulic conditions in the borehole.

3.4.1 Hydraulic conditions

A low rate injection test was conducted in order to characterise the hydraulic properties of the undisturbed reservoir and an intrinsic permeability of $\sim 1 \cdot 10^{-17}$ m^2 was estimated from the results for the open hole section. Indications of bilinear flow suggest that the flow regime is dominated by single fractures. The undisturbed Basel-1 reservoir can be described as a very low permeable granitic rock matrix containing few fractures with low fracture permeability causing bilinear flow (Ladner et al. 2007).

3.4.2 Geothermal conditions

Temperature gradient

The shape of the temperature log in the sedimentary section is non-linear, indicating variations in rock thermal conductivity and water circulation in individual fractures or layers. The mean geothermal gradient in the sedimentary section was calculated to 41°C/km.

The temperature profile within the crystalline basement follows a linear trend showing a mean geothermal gradient of 27°C/km. Perturbations in the temperature profile in the upper part of the crystalline basement (2,400–2,500 m depth) indicate the occurrence of water circulation.

A maximum temperature of 174°C was measured at 4,682 m depth assuming that the borehole had attained thermal equilibrium (Ladner et al. 2009). The values quoted above for the geothermal gradient are significantly higher than the approximately 15 ºC/km that is regarded as representative for the Fennoscandian shield (Juhlin et al. 1998, Ahlbom et al. 1995).

3.4.3 Rock mechanical properties

The Basel-1 borehole was drilled to 5,009 m depth and cased to 4,629 m below ground level. The borehole penetrated a 2,400 m thick sequence of Tertiary, Mesozoic and Permian sediments. The top of the granite was encountered at 2,426 m. The basement top consists of an approximately 100 m thick mixture of weathered pieces of granite and red siltstone. The underlying crystalline basement comprises exclusively plutonic rocks. No high-grade metamorphic rocks are present. The primary rock types are dominated by granitoid plutonic rocks (> 99%) (Ladner et al. 2007).

Fracture density is greatest near the top of the granite and declines with depth. This might reflect the fact that the top of the granite is a palaeo-weathered surface.

Borehole breakouts, which are present over some 80% of the log, provide valuable information for estimating the orientation of in-situ stresses and their magnitude.

Observations show that there are significant variations in stress orientation within the Basel reservoir, and that these variations are spatially correlated to natural fractures. Similar results have been observed in the Soultz geothermal field. The results also indicate that there are significant deviations of both total horizontal stress magnitudes SHmax and Shmin from linear trends with depth, and in many cases the perturbations are correlated with the location of natural fractures. The maximum horizontal stress increases with depth (Sikaneta and Evans 2012).

4 Discussion

The present study was initiated by SKB with the objective to update the general understanding of the conditions such depths in crystalline rock that would be relevant for the concept of disposing spent nuclear fuel in deep boreholes. This means boreholes with a depth up to about five km. The study started by identifying European boreholes that have been reported after the conclusion of previous appraisals (Juhlin et al. 1998, Smellie 2004). Out of 12 identified borehole sites, boreholes penetrating into crystalline rock were drilled only at four sites. These were:

- A 2,516 m deep borehole at Outokumpu in eastern Finland that was drilled as part of a geoscientific programme.
- A 3,701 m deep borehole in the vicinity of the city of Lund in southern Sweden that was drilled as part of a potential geothermal plant. The plant was subsequently closed due to a too low water yield.
- Up to 5,250 m deep holes at Soultz-sous-Fôrets in north-eastern France. The boreholes were drilled within a European programme for geothermal energy.
- A 5,009 m deep hole in the city of Basel in northern Switzerland. The hole was drilled for geothermal development.

It is worth noting that the only realistic location of a Swedish site for disposal of spent nuclear fuel in deep boreholes would be in flat topography areas of the Fennoscandian shield. Both the French and the Swiss boreholes listed above are located in areas with much stronger geothermal fluxes than those in the Fennoscandian shield. Moreover, these boreholes have not been exposed to the Nordic Quaternary climatic history including recurring glaciations. Both these factors may limit the relevance of these boreholes for the understanding of a potential site for deep borehole disposal.

The remaining two boreholes are located on the rim of the Fennoscandian shield. The hole at Lund is drilled in a geothermal context with an almost 2,000 m thick sedimentary overburden. Furthermore, the hole is located in the Tornquist zone that is a major tectonic zone along the border of the Fennoscandian shield. Also this context could be seen as atypical for deep borehole disposal.

Only limited data from the holes in France, Switzerland and the Lund area have been available during this study. There is a significant bibliography of data from the French hole that could not be penetrated during the present study. Due to the objective of these holes, much of the data available have concerned fracturing, temperature relations, water yield, etc. Both the French and the Swiss holes have been stimulated to increase the efficiency of the geothermal plants at the site.

The borehole with most relevance to deep borehole disposal in Sweden would then be the Outokumpu hole, although a major part of the borehole is drilled through meta-sedimentary rocks (mica-schist). This is also the most thoroughly investigated hole from a geoscientific perspective. In principle, the investigations show that, although there are conductive fractures at great depths (down the bottom of the hole at 2.5 km), the water in the fractures has been isolated from meteoric influences for a very long time. Despite this, the groundwater at this great depth appears to be of ancient meteoric origin with a chemistry that has developed through water-rock interaction rather than from metamorphic inclusions. The analysis suggests residence times for the deeper waters in the order of 10s of millions of years (Kietäväinen et al. 2013). The waters at depth are saline but that the salinity varies in a non-regular fashion. The conclusions from the analysis of the Outokumpu hole confirm the general conceptual model of the deep saline groundwater derived by Juhlin et al. (1998) and Smellie (2004). However, the results from the Outokumpu hole seem to more clearly explain the origin of the salinity in the deep groundwater than the earlier studies.

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