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The Very Deep Hole Concept – Geoscientific appraisal of conditions at great depth

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THE VERY DEEP HOLE CONCEPT - GEOSCIENTIFIC APPRAISAL OF CONDITIONS AT GREAT DEPTH

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VDH CONCEPT: GEOSCIENTIFIC APPRAISAL OF CONDITIONS AT GREAT DEPTH

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Keywords: borehole, fracturing, groundwater, salinity, Baltic Shield, deep drilling

Foreward

The review work in this report was divided into six disciplines:

Geology - Thomas Eliasson

Hydrogeology - Thomas Wallroth

Hydrochemistry - John Smellie

Geophysics - Christopher Juhlin

Geomechanics - Bengt Leijon/Christer Ljunggren

Drilling - John Beswick

Prior to the writing of this report, sub-reports on all disciplines except drilling were compiled by the individual researchers. These sub-reports formed the basis for the present report where an attempt has been made to integrate the various fields. The majority of this work was carried out during 1996. Since then, new results have been published from various deep drilling projects. However, the basic conclusions of this report are still considered valid.

Abstract

One of the alternative systems for disposal of high-level radioactive nuclear waste being studied by SKB is the very deep hole (2000 - 40000 m) concept.

As part of SKB's research programme a study has been carried out to increase the level of knowledge on the expected geological conditions in the depth interval 1000-5000 m in older crystalline rock. As a first step, existing data from relevant areas throughout the world have been compiled. The majority of the data come from deep boreholes, mines, and surface geophysical surveys. An attempt has been made to interpret these data in an integrated manner and to develop a conceptual geological model on the conditions in the Baltic Shield down to a depth of 5 km.

One of the main features of the suggested model is that the upper 1 km of crust contains significantly more open fractures than the rock below. However, hydraulically conductive fractures and fracture zones may exist at great depth. In areas of low topography active groundwater circulation is primarily limited to the upper 1 km with the water below 1 km having high salinity. The high salinity reflects the near hydraulically stagnant conditions which exist relatively shallow in areas of low topography. In areas with greater topographic relief fresh water penetrates to great depth and near stagnant conditions are first encountered much deeper.

The report also covers how the studied parameters which describe the geological conditions vary with depth.

A number of recommendations are made on how the presented conceptual model can be tested and improved aside from obtaining data from new boreholes. These recommendations include the following geoscientific surveys and studies:

- Reflection and refraction seismics for mapping discrete sub-horizontal fracture zones and the upper more fractured part of the crust
- Geoelectric methods for mapping the depth to saline water
- Detailed hydrogeological measurements in existing deep boreholes
- Isotope studies on fracture minerals from deep boreholes
- Earthquake studies
- Numerical modelling of large scale groundwater flow

Sammanfattning

Ett av de alternativa system för djupförvaring som studerats av SKB innebär deponering av kapslar i mycket djupa (2000 - 4000 m) borrhål.

Som en del i SKBs forskningsprogram har i kunskapsuppbyggande syfte en studie genomförts av de geovetenskapliga förhållandena på stora djup (1000-5000 m) i kristallin berggrund. En sammanställning och genomgång har som en inledande del i studien gjorts av tillgängliga geovetenskapliga data från relevanta geologiska miljöer i olika delar av världen. Dessa data baserar sig på undersökningar i djupa borrhål och gruvor samt på geofysiska, ytbaserade mätningar. Därefter har en integrerad tolkning av de olika typerna av data gjorts och en konceptuell geovetenskaplig modell av förhållandena ner till 5 km djup i den Baltiska skölden har föreslagits.

Den föreslagna modellen bygger på att den övre kilometern av berggrunden innehåller betydligt fler öppna sprickor än de djupare delarna. Vattenförande sprickzoner finns dock ner till mycket stora djup. I områden med förhållandevis flack topografi är aktiv grundvattencirkulation i huvudsak begränsad till den övre kilometern medan vattnet har relativt hög salthalt under denna nivå. Det mycket salta, djupa grundvattnet befinner sig i en nästan stagnant miljö. I områden med större topografiska skillnader kan sötvatten som infiltreras drivas ner till mycket stora djup och gränsen till salt vatten ligger betydligt djupare.

I rapporten dras även slutsatser om hur de olika undersökta parametrarna varierar mot djupet inom det studerade djupintervallet.

Ett antal förslag ges på hur den föreslagna konceptuella modellen skulle kunna testas och eventuellt förbättras i brist på flera djupa borrningar. Förslagen omfattar bl a följande geovetenskapliga mätningar och studier:

- reflektions- och refraktionsseismik för att studera flacka sprickzoner respektive djupet för den antagna zonen med förhöjd frekvens av öppna sprickor

- geoelektriska mätningar av djupet till salt grundvatten

- detaljerade hydrogeologiska mätningar i befintliga djupa borrhål

- isotopstudier på sprickmineral från djupa borrhål

- jordskalvsanalys

- numerisk modellering av storskaligt grundvattenflöde

Executive Summary

The Very Deep Hole (VDH) concept for storage of high level nuclear waste involves the drilling of large diameter boreholes to c. 4 km depth, placing the waste in canisters, and then deploying the canisters between c. 2 km to 4 km depth. For this concept, it is imperative that the geological conditions down to 5 km are fully understood. The initial step in making this appraisal was carried out in 1989 (Juhlin and Sandstedt, 1989) where a model suggesting that the upper c. 1-1.5 km of bedrock in the Baltic Shield is considerably more fractured (contains more open/hydraulically active fractures) than that below. This suggestion was based on a review of results from the Gravberg-1 drilling project and other deep drilling projects world-wide. The concept that the upper 1 km is more fractured than the rock below was earlier put forth by Båth (1985). Båth observed low velocities in the upper 1-2 km in seismic data (P-wave refraction and surface seismic wave data) and attributed these low velocities to fracturing. In the present study, the concept of increased fracturing in the upper c. 1 km of bedrock is further investigated by reviewing more recent data from other deep boreholes. The earlier work of Juhlin and Sandstedt (1989) concentrated mainly on geophysics and rock mechanics. The present study also includes these fields, but more effort has been put into understanding the geological, hydrogeological and hydrogeochemical conditions at depth. The review work was initially divided into the five fields:

- Geology
- Hydrogeology
- Hydrochemistry
- Geophysics
- Geomechanics

These initial reports, which include compilation, review and analyses of data relevant to each field, form the basis for an integrated study of the geological conditions down to 5 km. In this study an attempt is made to present a consistent model which takes data from the various fields into account. The data, which are mainly extracted from deep boreholes, cover the following parameters:

- Lithology and structural geology
- Fracture mineralogy
- Fracturing (porosity)
- Temperature
- Permeability
- Pore pressure
- Mechanical properties
- State of stress
- Fluid composition and bacteria
- Natural seismicity

A review of how continents evolve and the geology of Europe is included in the study since the geological setting of the boreholes studied varies greatly.

The work is primarily aimed at evaluating the geological conditions down to 5 km depth in the Baltic Shield. However, since deep boreholes are rare, we have used information from other areas as well. We also use data from deep mines and surface geophysics to complement borehole data. From the review the following can be concluded:

- Prediction of lithology at depth based on surface geological information is difficult in metamorphosed volcani-sedimentary rocks due to the heterogeneous lithology and, generally, more complicated tectonic history of these rocks. In granitic environments it is easier to predict the lithology in the upper 5 km.

- Fracture mineralogy is indicative of how an observed fracture evolved. If the minerals are in equilibrium with the surrounding rock then the fracture probably developed under ductile regional metamorphic conditions, otherwise it developed under brittle conditions. Brittle fractures are probably the ones which are most likely to be highly permeable.

- Surface and borehole geophysical data show that the degree of open fracturing decreases significantly below c. 1 km.

- Although data are sparse, large scale permeability also appears to decrease significantly below 1 km. In the available data, the large scale permeability is about 3 orders of magnitude lower at 5000 m than at 1000 m.

- In general, the pore pressure is close to hydrostatic in all boreholes reviewed. The one exception is the Kola borehole in the Baltic Shield of Russia where pore pressures of 40-50 % greater than hydrostatic have been reported in the depth interval 1000-2800 m.

- Mechanical properties of the rock are defined in terms of strength and deformability and studies carried out near the surface are relevant for quantifying the effect of increasing confinement pressure, i.e. increasing depth. The parameters are dependent on the volume of the rockmass under investigation.

- The stress appears to increase linearly with depth down to 5 km, although quantitative measurements below 1 km are lacking in the Baltic Shield. The vertical stress is generally the intermediate stress implying a tectonic regime dominated by strike-slip faulting.

- In general, pore waters are relatively fresh down to at least 500 m throughout Sweden, but become more saline below this depth. At great depth, brines are present. The depth to these brines appears to be dependent upon geographical location and hydrostructural controls. High gas content may be observed in brines in Sweden and Canada. The chemistry, isotopic character and high gas content shows that the brines have been stable for periods of millions to possibly hundreds of millions of years.

- Measurement and extrapolation of borehole data give a temperature gradient in the Baltic Shield of c. 15° C/km. These temperature gradients are also predicted in the uppermost crust from lithospheric modelling of heat flow in the Baltic Shield.

- Sweden has only, comparatively, minor earthquake activity. However, earthquakes on the order of magnitude 5, or even 6, in the future cannot be ruled out. Some of the observed earthquakes occur at shallow levels, in the upper 5 km of bedrock. There is currently a debate on the source of earthquakes, whether they are due to stresses from post-glacial rebound or to plate tectonics.

- Investigations show that bacteria exist and flourish at great depth, independent of the biosphere, and are able to produce large quantities of methane. This implies that previous interpretations of deep groundwater evolution may have to be somewhat modified.

The above results have been integrated into a conceptual model for groundwater flow and evolution in the upper 5 km of the Baltic Shield. It is suggested that the upper c. 1 km of crust contains significantly more open fractures than the rocks below, although fluid bearing fracture zones extend to great depth. The decrease in open fracturing below c. 1 km also corresponds to a decrease in rockmass permeability. In areas of low topography, active groundwater circulation is primarily limited to this upper 1 km with highly saline water or brines present at greater depth. Where topography is high, meteoric waters will penetrate below into the less fractured interval below 1 km and may circulate to depths as deep as 10 km. Evidence for this is found in the Gravberg-1 borehole in the Siljan Ring area where waters first became saline at about 5 km. These highly saline fluids are nearly stagnant and have probably remained in place on the order of millions to hundreds of millions of years. Evidence for this is reflected in the chemistry, isotopic character and in the high concentrations of dissolved gases in them.

Contents

1 INTRODUCTION

1.1 BACKGROUND

The currently preferred method for final disposal of highly radioactive nuclear waste in Sweden is the KBS-3 concept (SKB, 1992) which consists of a mined repository at about 500 m depth in crystalline bedrock. However, other options are also of interest, one of which is the Very Deep Hole (VDH) concept. An earlier report (Juhlin and Sandstedt, 1989) describes the technical details of the concept as well as the expected geological conditions in the depth range 2–4 km where the waste would be stored. The present work constitutes an extension and an expansion of the previous study concerning geological conditions in the depth range relevant for the VDH concept. It is based primarily on review of literature dealing with geological conditions in the depth range 1000-5000 m in shield areas and younger crystalline massifs which has been ongoing since 1993 (Juhlin and Leijon, 1995). However, a comparison with conditions shallower than 1000 m is also necessary. Much of the information obtained in the depth range 1000-5000 m is from deep boreholes.

The VDH concept (SKB, 1992) involves drilling 800 mm diameter boreholes to 4000 m, placing the waste in canisters, and then deploying the canisters between 2000 and 4000 m. For this concept, it is imperative that the geological conditions in the depth interval 1000-5000 m are fully understood. Tentatively, the concept consists of c. 40 large diameter boreholes (20 if the waste is consolidated prior to being placed in canisters) with an average spacing of 500 m. Each borehole will influence a rock volume on the order of 0.25x0.25x4 km^3 (Figure 1-1). In total, the VDH repository will directly affect a surface area of about 7 km^2 and a volume of about 28 km^3.

In the VDH concept the rock is the barrier so that the time for radio-nuclide migration to the surface will be so long that they will not pose a safety hazard. Furthermore, the long transport paths will also decrease the concentration of the nuclides due to interaction with fracture surfaces and the rock matrix. Thus, the natural conditions of the rock will form the primary barrier to migration. Rock conditions below 2 km in the Baltic Shield are expected to be favourable for a VDH repository for two reasons. First, the number of open fractures is suggested to be considerably less below 2 km than above 1 km. Secondly, where there is little topographic influence the groundwater is expected to be highly saline and stagnant on the order of tens to hundreds of millions of years. This latter factor can form an effective natural barrier and prevent any radionuclides from reaching the surface in the event of leakage.

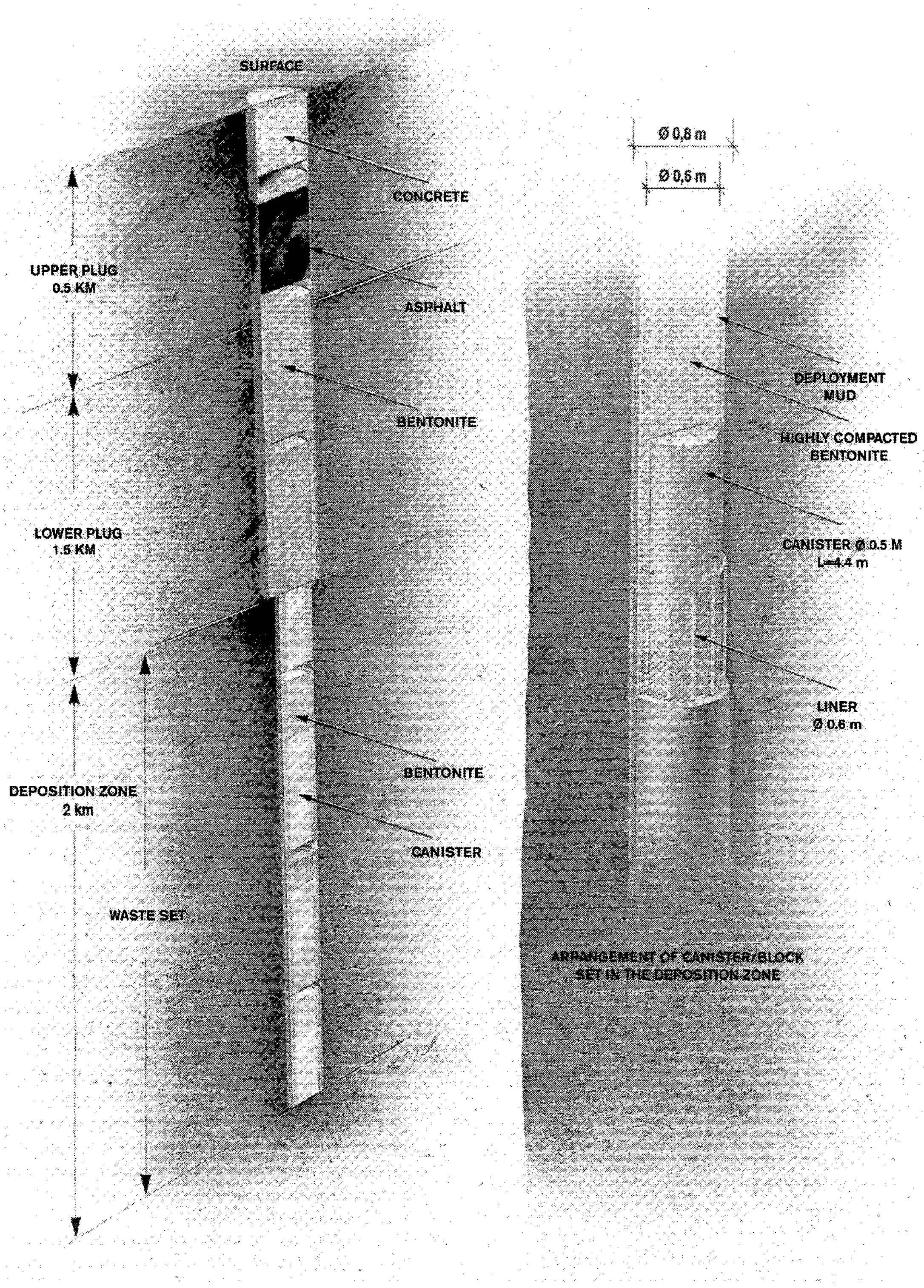


Figure 1-1. Schematic drawing of on hole borehole in the VDH system for waste disposal (from SKB, 1992).

1.2 CONSTRUCTION AND PERFORMANCE

Factors to consider in deploying waste using the VDH concept include

- Technology (drilling)
- Operational handling of the waste (transport, encapsulation, etc.)
- Retrieveability
- Expected developments

The technology to construct a VDH repository existed at the time of the previous report (Juhlin and Sandstedt, 1989). Since then some improvements have been made (see chapter 4), however, the basic concepts are the same. The waste for the VDH concept would be handled in a similar manner as for other concepts under consideration. Once the waste canister is deployed in the boreholes it will not be possible to retrieve it using the current VDH concept. Advances in drilling technology should continue at a moderate pace driven by the demands of the petroleum industry.

1.3 SAFETY

Safety is obviously important for any repository for nuclear waste. In addition to the short term safety considerations for when the waste is deployed in the vdh concept, the following longer term factors need to be considered (see for example birgersson et al., 1992)

- Leakage
- Human intrusion
- Climatic changes
- Earthquakes
- Long term environmental effects of the operations

Although no thorough assessment of safety is given in this report, it is worthwhile to point out that the chances of human intrusion and that climatic change can influence the conditions of the repository decrease significantly with depth. Leakage to the surface may be impossible under certain geological conditions.

2 OUTLINE OF PRESENT WORK

2.1 GOALS

The main goal of this study is to present a summary of expected geological conditions in the Baltic Shield in the depth interval 1000 m to 5000 m and compare these conditions with the interval from the surface to 1000 m. The geological conditions considered are:

- Lithology and structural geology
- Fracture mineralogy
- Fracturing (porosity)
- Temperature
- Permeability
- Pore pressure
- Mechanical properties
- State of stress
- Natural seismicity
- Fluid composition and bacteria

High priority has been given to direct observations of these conditions, i.e. boreholes and deep mines. However, the number of boreholes and deep mines in the Baltic Shield are few and, therefore, surface observations and borehole data from other areas than the Baltic Shield have been taken into account.

Irrespective of which geological disposal method is finally used by SKB, knowledge of the geological conditions in the continental crust in the depth interval 1000–5000 m is of importance for the long-term safety assessment. Factors such as the depth of circulation of meteoric water, depth distribution of natural earthquakes and fluid composition in the depth interval 1000–5000 m may influence the potential migration of radionuclides from a shallower storage site to the surface.

2.2 GEOGRAPHIC PRIORITY

The study examines information from many geographical areas. All data examined have not been included in this report, since the volume would be too great and much of it has only minor relevance to the Baltic Shield. Data and reporting have been given the following geographic priority:

1. Baltic Shield

2. Other recently glaciated shields

3. Other areas with relevant data

Many of the observations on the Baltic Shield may be influenced by recent and ancient glacial events and, therefore, areas such as the Canadian Shield are considered highly relevant for obtaining information in the depth range 1000–5000 m.

Given the numerous deep boreholes in the former Soviet Union (FSU), SKB commissioned NEDRA (the Russian Deep Drilling company) to review results from three boreholes in the FSU (NEDRA, 1992). Two of the boreholes reviewed, the Kola and Krivoy Rog boreholes, are drilled in Precambrian shield areas. These boreholes are highly relevant for the current study.

2.3 THE UPPER 1000 M VS. THE INTERVAL 1000-5000 M

Båth (1985) proposed that there exists a zone of lower velocities in the upper few kilometres throughout the shield area of Sweden based on observations from refraction profiles and short-period Rayleigh wave studies. Båth (1985) refers to data from other shield areas in Finland, Canada and the USA where similar patterns are observed and concludes that a zone of low velocities in the upper few kilometres is characteristic of shields in general. These low velocities have been attributed to increased open fracturing in the upper part of the crust. Note that (Brotzen, 1986) argued against Båth (1985) and refers to results from shallow coreholes (down to 1200 m) which do not show an increase in the sonic velocity with depth. In the earlier report (Juhlin and Sandstedt, 1989), the hypothesis of increased fracturing in the upper 1-1.5 km of crust was studied in more detail by examining results from deep drilling projects. Although the studies were not quantitative there were strong indications that the upper km or so, in many areas, is more fractured, or contains more open fractures. The original proposition by Båth (1985) of increased fracturing in the upper kilometre of crust is further studied in this report.

3 GEOSCIENTIFIC PARAMETERS

3.1 RELEVANT DATA

3.1.1 Lithology and structural geology

When compiling lithological and structural data the following parameters have been considered:

- rock types
- metamorphic grade, i.e. the intensity of metamorphic alteration indicated in a general way by the pressure and temperature environment in which the metamorphism took place
- primary and ductile structures (e.g. intrusive, depositional, metamorphic, and tectonic), including the degree of foliation, frequency of ductile shear zones etc.
- brittle structures, i.e. fractures and fault zones, and their general characteristics, such as orientation, frequency, type of fault rock and fracture mineralisations, and rock wall alteration

In general, geological information (principally lithological and structural data) is used to construct conceptual geological models which are important foundations for understanding, characterisation and modelling work on groundwater flow, groundwater chemistry and rock mechanics. For example, these parameters have great effect on the strength and deformability of the rock, which are critical both for the drilling operation and for the long-term performance of the repository. The technical performance and overall costs of the drilling are likely to be dependent on the geological parameters listed above. Furthermore, it is not uncommon that there are correlations between rock type and the degree of fracturing as well as the bulk permeability of the rock.

3.1.2 Fracture mineralogy

Within the upper brittle crystalline continental crust, fluid transport is predominantly restricted to fracture and fault zones. The space within fractures may be filled with minerals (precipitating from fluids entering the fractures), whose composition and growth reflect the conditions in the fracture. The minerals may be in equilibrium with the surrounding host rocks and show more or less the same mineralogy. This type of features are referred to as diagenetic features in NEDRA (1992). These fractures and veins, considered to be developed during the lithification or metamorphic event, are often parallel to the main foliation in the host rock. However, more often, the brittle fracture network in magmatic and metamorphic rocks is filled with minerals out of equilibrium (formed at lower temperatures) with the host rocks, as well as earlier diagenetic vein mineralisations, and show a mineralogy, which reflects solely the conditions within the fracture during the crystallisation of the fracture filling minerals (tectonic fractures according to the NEDRA (1992) nomenclature). The fracture filling mineralogy and crystallisation sequences can provide information on the palaeo-fluid activities in the fracture. Thus, fracture mineralisations may supply information about the tectonic and hydraulic history of the rock (e.g. Landström and Tullborg, 1995).

Fractures and fracture zones are frequently associated with alteration zones (hydrothermally metamorphosed rock and/or rock affected by low temperature alteration or weathering) occurring in the host rock parallel to the fracture planes. The width of these alteration zones may vary from centimetres up to tens of metres. The petrophysical properties of these alteration zones may differ from the neighbouring unaltered host rock (Eliasson, 1993; Mazurek et al., 1997).

Common fracture filling and alteration minerals are, for example, quartz, chlorite, calcite, epidote and prehnite. Fe-oxyhydroxides are commonly found in oxidising environments (near surface) whereas sulphides may be present in reducing (more deep seated) environments.

Large faults are commonly characterised by zones of ductile and/or brittle deformed rock. The mineralogy and texture of these *fault rocks* (dynamically and hydrothermally metamorphosed) are highly different from the adjacent host rock. Furthermore, these reactivated fault rocks commonly constitute the walls of presently hydraulically conductive fractures (Mazurek et al., 1997) and thereby influence radionuclide retention properties along the fractures. Fault rock formed under ductile conditions, i.e. mylonites, generally have a mineralogy fairly similar to their predecessor (protolith). Incohesive (unlithified) fault rocks such as fault gouge and breccia generally have highly modified mineral compositions (due to pervasive low temperature alteration) with a very high clay mineral content.

The composition of the fracture filling material and fault rocks present in hydraulically conductive fractures has important bearing on the sorptive and diffusive properties as well as on the mechanical properties of the fracture.

3.1.3 Fracturing (porosity)

Intact crystalline rocks contain very little pore space (Öquist, 1981; Stenberg, 1986; Mazurek et al., 1997) and have typical porosities of 0.1-0.5% (ratio of total pore space to total volume). The physical properties of intact rocks are governed primarily by the mineral composition of their matrix and the in-situ stress conditions. On the other hand, the physical properties of rocks which are fractured are heavily influenced by the fracture pore space and the material within it. Fractured crystalline rocks may have up to 10% bulk porosity or possibly even more (Juhlin, 1990; Juhlin et al., 1991) along with very high permeability. It is almost certainly along these fractured zones that fluid transport occurs and where stress is released through seismic and aseismic activity.

It is relatively straight forward to measure porosity on a core sample. However, large friable fractures are often not sampled in the coring process and in highly fractured zones core is usually not recovered or it is not possible to make measurements on the recovered core. Therefore, indirect methods, such as geophysical logging, may provide important estimates of the porosity in the most interesting zones. Geophysical logging (e.g. TV, microresisistivity and televiewer logging) is also a nearly continuous sampling method and gives a more complete log of the degree of fracturing in a borehole than is normally possible through coring. Surface geophysics may also give some very rough estimates on the degree of fracturing in the depth interval 1000-5000 m. See Juhlin (1996) for a brief review on how fracturing influences geophysical measurements.

Observations in Sweden (Juhlin, 1990) and elsewhere (Moos and Zoback, 1983) show a strong correlation between low P-wave velocities and the presence of fluid filled fracture zones in boreholes. It is generally accepted that fluid saturated fractured crystalline rock will have lower velocity than intact rock. If fractures are sealed with minerals then the velocity difference may be considerably less.

3.1.4 Temperature

The temperature will have great influence on the location of deep repository since the proposed sealing material, bentonite, should not be subjected to temperatures above 120°. In addition, the temperature field will influence pore water circulation patterns once the waste has been deposited. Although the temperature gradient is generally low in the Baltic Shield, there is some variation from south to north (Balling, 1995).

3.1.5 Permeability

Permeability is a measure of the capacity of a medium to transport fluid through its pore space. It is a property of only the medium and independent of the properties of the fluid. *Hydraulic conductivity* is also a measure of the transport capacity, but is dependent on the fluid's density and viscosity.

The water-bearing characteristics of the crystalline basement depend upon the presence, aperture and connectivity of open fractures and fracture zones. A commonly used approach to estimate flow and transport in such fractured media is to assume an equivalent porous media, i.e. the rock mass is considered as a continuum and not as a set of discrete fractures. This approach assumes that a representative elemental volume (REV) can be defined within the scale of the system being examined. Experiences from a number of in-situ studies have demonstrated that there is a pronounced scale effect in the hydraulic characteristics of crystalline rock masses. The variation in the hydraulic properties can be significant between different lithological units and different depths. A world-wide compilation of in-situ measurements in crystalline bedrock made by Clauser (1992) reports a permeability range of 10^{-20} - 10^{-12} m^2. As a comparison, permeability values associated with micro-cracks, as measured in the laboratory on intact rock samples subject to stresses corresponding to deep in-situ conditions, are in general lower than 10^{-20} m^2. This means that the crystalline rock matrix for most practical applications can be considered impermeable.

In general, the analysis of a hydraulic in-situ test carried out in a section of a borehole yields a value of the *transmissivity*, corresponding to the product of the conductivity and length tested. For comparison of the capacity of different rocks to transport fluid, the preferred unit of measurement is permeability since it is independent of both the pore fluid properties and the length of the section tested. However, as a consequence, these values of permeability are bulk values representative of different volumes of rock and do not generally describe the properties of single fractures or fracture zones.

3.1.6 Pore pressure

The pore pressure in fractures and fracture zones will influence the mechanical stability of a borehole during drilling and possible later radionuclide migration. In old shield areas the pore pressure can be expected to be close to hydrostatic. However, in areas close to significant topography or below the maximum depth of meteoric water circulation the pore pressure may deviate from hydrostatic.

3.1.7 Mechanical properties

The most significant mechanical properties of crystalline rocks are strength and deformability. A variety of parameters are used to describe strength and deformability under different modes of loading. Knowledge of these parameters is required in order to assess mechanical stability, which is of concern for several reasons. Irrespective of repository system used, long-term integrity of engineered barriers such as canisters and clay buffers relies to some extent on the bedrock environment remaining mechanically stable over long periods of time. The same applies to the barrier function of the rock itself. The location, magnitude and nature of potential fault plane movements are examples of factors that need to be considered in this context. Furthermore, stability is also of concern with respect to the feasibility of constructing and operating repository systems. For the VDH-concept, borehole stability at large depths is an important factor for both demands on drilling technology and the feasibility of waste emplacement.

In principal, strength and deformability depend on:

- The rock material as such.
- Geometrical parameters such as volume and shape.
- Boundary conditions, in particular, confinement and temperature.

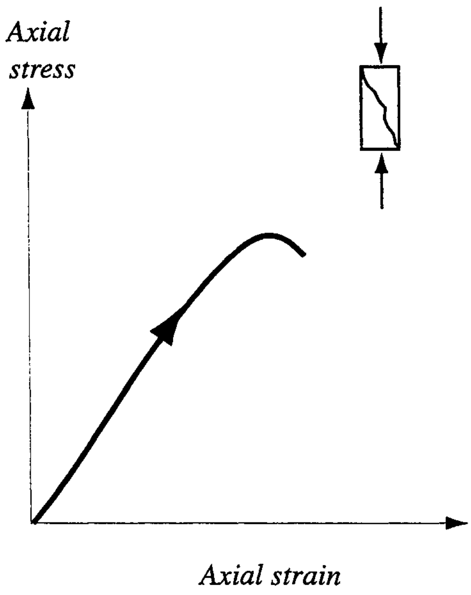


Figure 3-1. Typical stress-strain curve obtained from uniaxial compressive loading of a specimen of crystalline rock.

Depending on the problem studied, it may be relevant to consider the strength and deformability of the intact rock or individual discontinuities. Parameters of intact specimens can be inferred from stress-strain curves such as the one shown in Figure 3-1. The uniaxial compressive strength, σ_c, is defined by the peak of the curve. Deformability, defined as the slope of the curve, changes with load applied, and can therefore only be defined at specific points. The modulus of elasticity, E, and Poisson's ratio, ν, are commonly used approximations to characterise deformability over the load interval where the stress-strain curve is more or less linear.

In most applications, however, one has to consider the overall rock mass properties, reflecting contributions from both intact material and discontinuities. Increasing the volume of rock being subjected to loading implies that an increasing number of discontinuities, of gradually larger size, become involved. It follows then, that parameters describing strength and deformability are scale dependent, which have major implications in rock engineering. Generally speaking, scale-dependency is more pronounced for strength than for deformability.

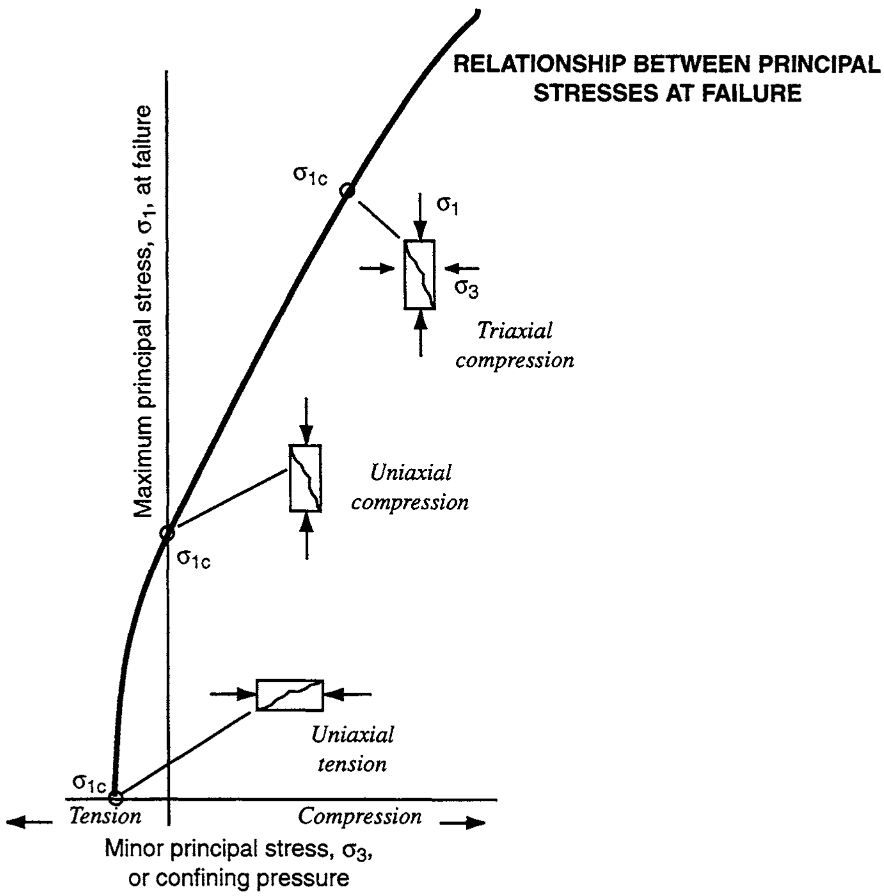


Figure 3-2. A failure envelope illustrating the effect of confinement stress on strength. Points represent the loading modes for uniaxial tension, uniaxial compression and triaxial compression.

Strength and deformability also depend on confinement. Figure 3-2 shows a failure envelope obtained by testing intact rock specimens under different modes of confinement. Besides significantly altering the strength values as such, different modes of failure will occur for different loading patterns. Confinement, therefore, plays a key role in all geomechanical problems involving stability, whether the concern is with engineered structures e.g. boreholes, or with large scale, natural phenomena such as fault movements.

3.1.8 State of stress

Knowledge of the state of stress is obviously a prerequisite for assessing stability. Experiences from deep drilling projects show that within the depth range 1000-5000 m, high and/or anisotropic stresses can generate failure of borehole walls (breakouts). This has significant implications on drilling possibilities and drilling technology. Long-term bedrock stability is another concern in which the state of stress (including possible changes with time) has to be considered. For example, the state of stress will determine on what fault planes movement will occur as the stress differential across fault planes changes with time.

Besides governing stability, the state of stress also affects other parameters. As mentioned above, strength and deformability are strongly stress-dependent. Hydraulic properties are also to some extent stress-dependent.

The in-situ stresses that exist in a rock mass are related to the weight of the overlying strata and in a complex manner to current and past tectonic loadings. To completely define the state of stress, six independent variables must be determined. With a few exceptions, data from stress measurements in the Baltic Shield are limited to the depth interval 0-1000 m. However, indirect measurements such as earthquake fault plane solutions (Slunga, 1981), borehole breakouts (Stephansson et al., 1989) and data from the deep Gravberg-1 borehole provide some constraints, as does extrapolation of shallower data.

3.1.9 Natural seismicity

Earthquakes result from build-up of stress in the crust due primarily to plate tectonics. However, in the Baltic Shield, post-glacial rebound also influences the stress field. Which factor, rebound or tectonics, that is the dominant cause of earthquakes observed at present in the Baltic Shield is currently being debated (see Muir-Wood, 1993; Slunga, 1997). When the shear stress exceeds a critical level the rocks on opposite sides of the fault plane slip in opposite directions. This slip velocity is in the range of 0.01-2 m/s (Boatwright and Cocco, 1996) with displacements on the order of 0.1 m (Slunga, 1997) for earthquakes with magnitude on the order of 4. This slip is generally believed to occur along pre-existing fracture or fault zones. Aside from the danger that a fault plane cuts through a repository, the seismic waves generated by an earthquake are a potential hazard to a repository. Shallow earthquakes are a more serious threat than deep earthquakes since they generate high amplitude Rayleigh or surface waves.

The first recorded historical earthquake in the Baltic Shield occurred in 1375 (Ahos and Uski, 1992). In 1904 the first seismometer was installed in Uppsala and since 1950 a sparse network of stations has been in operation in Sweden. This sparse network has been complemented by denser networks for shorter time periods. At present, only large earthquakes (magnitude greater than 3.0; Muir-Wood, 1993) can be monitored without bias since there is no dense recording network operating in Sweden. The largest recorded earthquake in the Baltic Shield occurred in the Oslo Graben in 1904 and had a magnitude of 5.5. The largest recorded earthquake in Sweden occurred in the Skövde area in 1986 and had a magnitude of 4.5. However, palaeo-seismic studies indicate that much larger earthquakes occurred in northern Sweden shortly after the glacial ice retreated (Lagerbäck, 1979; Lundqvist and Lagerbäck, 1976). Earthquakes occurring in the crust with a magnitude of 5 will produce moderate damage while ones with magnitude less than 3 will nearly go unnoticed by humans (Fowler, 1990).

3.1.10 Fluid composition and bacteria

The chemical composition of the pore water is an important parameter in both the drilling phase of a deep borehole and the capacity of the surrounding rock to maintain the integrity of the engineered barrier system and to retard transportation of radionuclides to the surface in the event of canister leakage. In the Canadian and Baltic Shields, brines (here defined as > 100 000 mg/L) have been encountered in the deeper boreholes (Fritz and Frape, 1982; Juhlin et al., 1991). In the event of canister leakage the high density of the brines will tend to act as a barrier to radionuclide transport to the surface if the waste is stored sufficiently far below the upper surface of the brine (Claesson, 1992). On the other hand, however, the presence of brines may be detrimental to the long-term stability of the canister and bentonite buffer materials. In addition to the dissolved solids in the pore water, deep brines may contain high levels of dissolved gases (Juhlin et al., 1991), or even free gas. These gases will influence both drilling and disposal conditions.

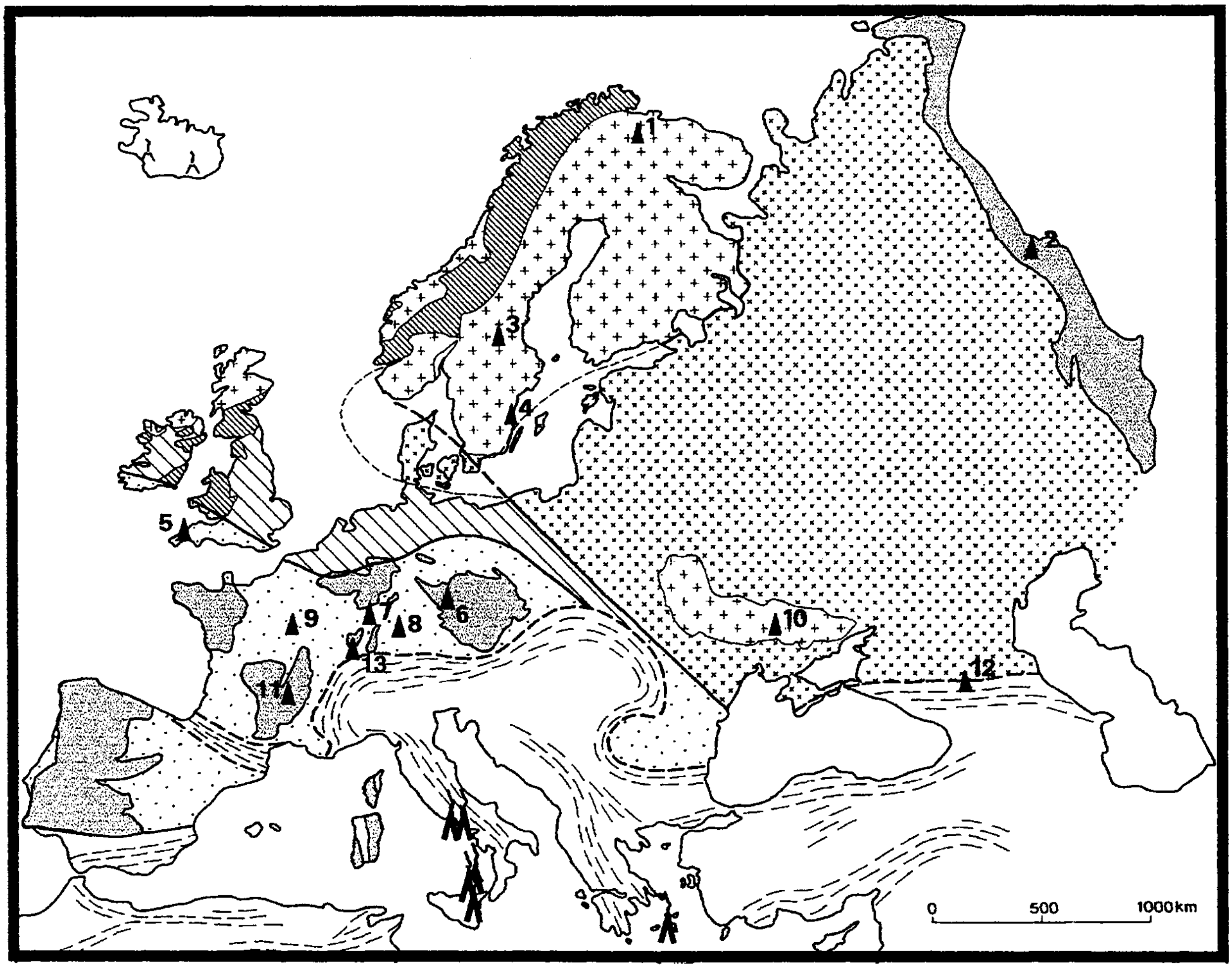
The presence of microbes in and around a repository for radioactive waste may also influence both the short-term and long-term performance and safety of a deep repository. For example, bacterial mediating reactions (e.g. iron oxidation and sulphate-reducing processes) may play an important role in the evolution of the groundwater chemistry, which may influence the groundwater redox conditions in the near-field and ultimately the integrity of the engineered barrier system. Because of these potential repercussions, studies in this field during the last 5-10 years have led to the detection and a greater understanding of the role of different types of subterranean bacteria. The results have shown a prolific abundance of different bacteria types to depths of at least 1000 m (West et al., 1986; Pedersen, 1989; Pedersen and Karlsson, 1995).

3.2 SOURCES OF DATA

3.2.1 Deep boreholes

Deep boreholes in crystalline rock are relatively rare. However, drilling incentives such as geothermal energy recovery, mineral prospecting and scientific drilling have resulted in a number of interesting boreholes in crystalline rocks. Many of these boreholes extend to depths on the order of 5 km and the data from them are highly relevant to this study. The deepest borehole drilled in the world is located in the Baltic Shield on the Kola Peninsula (Figure 3-3). It reached a total depth of 12261 m and is currently cased to 8270 m and open to 8578 m (Khakhaev et al., 1996). Drilling has ceased and the hole has been turned into one of two deep geo-laboratories in Russia.

Much of the data presented in this report are from deep boreholes, however, it should be kept in mind that drilling, logging and sampling at large depths is associated with major technical difficulties. This can severely affect data quality and care must be taken to fully assess the background and experimental conditions associated with the data.



Alpine Orogeny

Alpine sedimentary deposits

Alpine orogeny (80 Ma-present)

Hercynides (Variscides)

Phanerozoic cover

Hercynian orogeny (400-280 Ma)

Caledonides

Phanerozoic cover

Caledonian orogeny (430-390 Ma)

East European Craton

Phanerozoic cover

Precambrian shields (>570 Ma)

Active Volcano

Deep Borehole

1) SG-3, Kola
2) SG-4, Ural
3) Gravberg-1 and Stenberg-1, Siljan Ring
4) KLX02, Laxemar
5) RH11, RH12 and RH15, Cornwall
6) KTB
7) GPK-1 and GPK-2, Soultz-Sous-Forets
8) Urach-3
9) Sancerre-Couy
10) SG-8, Krivoy Rog
11) Cezalier
12) Tyrnaus
13) Böttstein

Figure 3-3. Major structural units of the European continent and locations of deep boreholes of interest.

3.2.2 Deep mines

The deepest mines in Sweden, and within the Baltic Shield, currently reach down to about 1000 m. However, abroad there are many mines that extend to 2000-4000 m. The deepest mines are found in the gold districts of South Africa, where excavations have been created down to some 4200 m. The Canadian Shield hosts several mines with depths of about 2500 m.

Data and experience from deep mining represent a very large body of well verified information on conditions at depth, especially regarding geomechanical conditions. As an example, the parameters and mechanisms governing fault slip have been extensively studied over several decades because induced fault movements that may involve seismic energy release is a serious threat to safety and operation in many deep mines.

Data from deep mines are however much more difficult to access and interpret than information from deep boreholes. The main reasons are that:

- mining related geoscientific investigations are usually aimed to support an industrial production process - not to produce research results as such. This affects research issues focussed upon as well as documentation and publication of results,

- mines are often situated in bedrock with odd geological conditions, to which should be added the man-made disturbance imposed by mining itself. Results are therefore highly site specific.

Compilation and generalisation of data must therefore be preceded by in-detail assessment of the mine-specific conditions and history related to each case study.

The only information retrieved from deep mines for the present study are data on rock stresses, originating from mining districts in Ontario, Manitoba and Quebec in Canada. Most of the sites are located in the Superior and Southern tectonic province of the Canadian Shield.

3.2.3 Surface geological and geophysical studies

Since boreholes and mines to deeper than 1000 m in crystalline rock are rare it is necessary to use information from more indirect methods to study the upper crust. Surface geological and geophysical studies are such indirect methods.

3.2.3.1 Extrapolation of surface geology

In contrast to parameters such as porosity, hydrochemistry and stress conditions, lithological and structural data are basically insensitive to the exhumation process, such as erosion of overlying rock or tectonic removal of overlying rock by extension. However, exhumation will probably affect parameters related to fracturing, as well as the composition of recent, low-temperature fracture filling minerals in hydraulically open fractures. Consequently, exhumed geological terrains from different crustal levels have traditionally been used to infer the conditions at depth in the crust. Studies of exhumed crust combined with geological results from deep boreholes drilled, at least partly, in crystalline bedrock provide a fairly good data base on the geology at depth within different geological terrains.

3.2.3.2 Seismics and other surface geophysics

In *reflection seismic surveying*, a source, i.e. an explosive, is activated at the surface generating seismic waves that propagate downwards and reflect back off discontinuities in the rock which are then recorded on the surface by geophones. Whether a reflection is observed on the surface depends on many factors including the impedance contrast (density and velocity differences) of the discontinuity, the lateral extent of the discontinuity, the thickness of the discontinuity, its dip and the signal quality. Reflection seismics is mainly an imaging tool and the method's strength lies in the high resolution it provides of the subsurface.

As opposed to reflection seismics, *refraction seismic surveys* provide direct measurements of velocities in the subsurface and the results can, therefore, be more readily related to the rock properties. However, resolution of discontinuities is much poorer than in reflection seismics. Refraction studies often make use of compressional (P) and shear (S) body waves (waves propagating in the interior of a solid), but surface waves are sometimes also analysed. Normally, only the first arrival times are used in determining the velocity-depth model, however, the arrival times of other refracted and reflected phases can be included, if present, to better constrain the model. In addition the amplitude of the arrivals may be analysed to construct an attenuation or Q model. Surface wave methods use the waveform of the Rayleigh wave and its dispersive properties to constrain the S-wave velocity depth function.

Gravity and magnetic measurements are generally displayed as a 2D field over the surface. The field measured at the surface is dependent upon the rock properties at depth. Magnetic maps are particularly useful for locating linear near-vertical features such as dolerite dikes or large fracture zones as well as for carrying out normal geological mapping.

Heat flow is determined by measuring the temperature gradient in a borehole and multiplying it by the thermal conductivity of the drilled rocks. The heat flow values and measured temperature gradients may be used to predict the thermal field at depth. Complicating factors in the determination of the true temperature gradient are climatic and hydrogeological influences.

Electrical methods have been used for several years to determine the gross conductivity structure of the crust. The frequencies used are relatively low implying that the resolution is poor. By using an artificial source the frequency content of the electromagnetic waves can be increased and offers the possibility of mapping the depth to which more saline fluid is present in the bedrock.

Seismological observations of earthquakes is potentially the most useful surface geophysical tool for obtaining information about the depth interval 1000-5000 m. Not only are fault zones located, but the active ones can be monitored giving information on the state of stress. There exists extensive databases over earthquake locations in the Baltic Shield, but the accuracy is generally too poor for extracting information about the interval 1000-5000 m from it. At best, the epicenters will be located to within an accuracy of 1 km, while the depth estimate can be off considerably more. Although accurate depth information is normally not available from seismological data, the source mechanism can often be determined and the directions of the principal axes of stress, the associated stress drop and the fault radius estimated.

3.3 UNCERTAINTIES IN DATA AND INTERPRETATIONS

There are a number of different uncertainties which need to be con-sidered when evaluating the geological conditions at depth. These include:

- Conceptual uncertainties
  - Variability
  - Heterogeneity/anisotropy
  - Scaling effects
- Measurement and sampling errors
- Subjectivity in interpretation

Evaluating the accuracy of the data presented in the literature is difficult. However, a general statement can be made stating that the deeper the measurement is from the less accurate it is. This will be true for "direct" borehole measurements such as sonic logging or hydraulic conductivity tests as well as for surface geophysical estimates of conditions at depth. Within the area of hydrogeochemistry, the great borehole depths imply risks of contamination resulting from difficulties in the sampling methods and the long-term sampling/transport times.

A general source of error for the interpretation of geoscientific data from the deep boreholes reviewed is the fact that these holes have been drilled more or less vertically. Due to the vertical sampling in the boreholes, the observed number of fractures with steep dips are considerably underestimated. This will have effect not only on the statistics of measured fracture populations, but also on secondary parameters such as permeability.

It is relatively common that different hydraulic test methods can give permeability values of a specific test section differing as much as 1-2 orders of magnitude. The conversion between different units of measurement entails an uncertainty due to the, in many cases, unknown composition and temperature of the pore fluid.

Actual stress measurements conducted by use of either the overcoring or the hydraulic fracturing technique normally give error levels less than 20%. In the present case, with no Swedish data at depth, except for estimations obtained from extrapolation of shallow data (< 1000 m) together with a few data points from deep measurements around the world, it is obvious that estimates on the stress field down to 5 km depth is highly uncertain.

Regarding the strength and deformational characteristics of the rock the effect of confinement is well understood from a large amount of laboratory testing and there is no reason to believe that rock in-situ should behave different from what is seen in the laboratory. This argument is of course only applicable as long as intact rock is studied.

In seismic prospecting for oil, it is not uncommon to predict the depth to a certain formation located at a depth 2-3000 m to an accuracy of 5 m (<1% error). However, this is in mature areas where there is abundant borehole control and detailed seismic surveying. The accuracy of the seismic velocity models for the upper crust is probably within 5%. That is, for a given lithology, a velocity decrease of 0.3 km/s may be considered to be significant and indicative of increased fracturing. Even for the very direct methods of obtaining information such as logging, coring and fluid sampling, there is a decrease in the accuracy with depth. This decrease can be due to such factors as poorer borehole conditions, increased uncertainties in the depth of the sampling and mixing of drilling fluid with pore fluid.

The presence of highly fractured zones at depth gives rise to difficulties in acquirung data in these zones due to core losses etc. As a consequence, very limited geological information may be obtained from many of the zones having the highest fracture frequency and thereby higher permeability.

In order to visualise the virgin conditions of the degree of fracturing at depth in the bedrock it is important that only natural fractures, open and/or healed, are included in the data. The data presented from some boreholes reviewed includes artificial, drilling induced fractures. For example, observations on cuttings from KTB-HB show that at certain depth intervals below 3570 m, severely microfractured cuttings predominate. These micro-cracks are not mineralised and are interpreted to have been induced as a result of stress release. Furthermore, most compilations do not differentiate between open and healed fractures, a fact that considerably reduces the value of fracture counts for characterising porosity at depth.

The uncertainty in the measurements on the geological conditions can be roughly estimated. However, the uncertainty in the interpretations and models we present is more difficult to constrain. This uncertainty will be discussed in more detail in chapter 15 after the data and interpretations have been presented and discussed.

4 DRILLING TECHNOLOGY

4.1 BACKGROUND

The VDH concept was first researched by Woodward-Clyde Consultants for the Office of Nuclear Waste Isolation, USA in 1983 (ONWI-226). The original studies carried out for SKB (Juhlin and Sandstedt, 1989) included a review of previous experience of deep (to 5 km) and super-deep (> 5km) drilling in crystalline rock. Deep and very deep holes in these rock conditions were almost entirely drilled for geoscientific or geothermal research purposes and the experience at that time included several super-deep boreholes in the former USSR which had not been reported on in detail in the west. The database also included the c. 7 km deep Gravberg-1 borehole drilled in central Sweden to investigate the presence of abiogenic gas in the Siljan Ring, Dalarna. Large diameter boreholes or shafts have been drilled for many years in various rock formations for mining and geoscientific research with diameters up to at least 6 m. Depths have been modest and the larger 4 m to 6 m shafts have not generally been drilled deeper than 1000 m.

Since 1989, there have been limited deep and super-deep geoscientific drilling, but data from the work carried out in the former USSR have been reported on in the public domain. In Sweden, a further deep exploration borehole was drilled in the Siljan Ring, known as Stenberg-1, in broadly similar conditions to those experienced in Gravberg-1. In addition, the KTB super-deep borehole has been drilled to a depth of 9101 m at a site in Bavaria, Germany which has provided one of the most comprehensively reported examples of very deep drilling in crystalline rock. This project also resulted in the development of some of the technologies needed to implement a major drilling campaign for waste storage while at the same time confirming many of the facets of very deep drilling in crystalline rocks experienced by other workers and reported previously.

In the UK and France, there have been significant programmes to investigate potential sites for underground mined repositories for radioactive waste disposal which have given an opportunity to refine and apply some of the geoscientific investigation and testing methods at depths down to 2000 m. In the UK, high quality coring and sophisticated hydrogeological testing has been carried out to 2000 m over a period of seven years (Ball et al., 1995; Beswick et al., 1992).

Other work has been done by Sandia Laboratories in the USA to address advanced drilling systems (Pierce et al., 1996) and to review the novel drilling methods used in the days of the former USSR for their superdeep program (Eskin et al., 1996).

During the period from 1989 to date, the oil and gas industry has been experiencing some significant developments, mainly in high angle directional drilling and long reach drilling. A record 8 km was achieved at the Wytch Farm Oil field site in England and a 10 km extended reach programme is in the planning stage (Gammage, 1997).

Again the last few years have seen the development of some new generation drilling rigs with mechanical handling systems and part automation both for offshore and for onshore. The special rig designed for the KTB superdeep project has in part acted as a catalyst together with the demands of the North Sea to generate some new rig building for the first time in 15 years. These new generation rigs offer better control, safer and faster operation and more emphasis on fit for purpose design (Boering and Swart, 1997).

This brief update addresses various relevant aspects of the original report (Juhlin and Sandstedt, 1989) and highlights in particular any significant new knowledge and the implications that this may have on the conclusions.

4.2 DEEP CONSTRUCTION: NEW INFORMATION

Since 1989, there have only been a few significant projects reported on which have added new knowledge to the database of deep drilling in the depth interval 1000-5000 m. Most notable is "Das Kontinentale Tiefbohrprogramm der Bundesrepublik Deutschland" (KTB) project where the main exploration borehole (HB), was completed to a depth of 9101 m in October 1994. The borehole had taken some 1468 days to drill which includes all time spent on scientific programmes and coring (an average of 6.2 m/day) (Boering and Swart, 1997).

The KTB programme has provided a significant amount of detailed data on many aspects of deep drilling and is well reported, However, in general terms, the experience of the KTB project does not add significantly to the knowledge already available at the time that the initial study for SKB was undertaken.

However, there was one significant engineering development in the KTB borehole which has direct relevance to any deep drilling and is an important development in this context. As part of the programme, two vertical drilling systems (VDS) were first tested then developed for use in the deep borehole, one of which was eventually selected for use throughout the drilling until such time as the downhole temperature was too great for the instrumentation and batteries in the device to function. To achieve very deep hole drilling successfully, it is vital that the hole verticality is controlled to minimise torque and drag forces and optimise the tensile capacity of the drill string. This is especially true where stress conditions introduce directional bias into the advancement process during drilling as with strong granites, or in complex bedding geology. Both inclination and azimuth changes have serious impacts on the construction of a deep borehole.

Without an active steering system, the trajectory of a deep hole once deviated from the vertical is very difficult to control and the tendency is for the hole to deviate severely in the direction of the least principal stress modified by the lithology and structural setting of the site. This was the case at Gravberg-1 where no directional control was used and once the well trajectory had deviated a few degrees from the vertical it was impossible to implement any control by the use of directional drilling assemblies.

Not only does verticality control assist the drilling process, it is vital to achieve a quality borehole with minimum tortuousity to allow casing to be run without difficulty. Boreholes with high tortuousity or doglegs pose special problems which would be particularly difficult for large diameter casing systems.

For the KTB project, a VDS was developed and applied. It consisted of a non-rotating housing containing the sensors for measuring the inclination, the electronics and the magnetic valves controlling four extendible rib stabilisers. An integral part of the system is a positive displacement mud motor (PDM) rotating the bit by means of a shaft through the housing. All of the four steering ribs are loaded by the hydraulic pistons with the same force. The ribs act in this case as springs and tend to stabilise the tool in the centre of the borehole. When a deviation from the vertical is measured by the sensors, the electronics close the magnetic valve of the corresponding rib, the hydraulic piston is cut off from the drilling fluid which was pressurising it before. The rib becomes unloaded and recedes under the action of the opposite, still loaded rib to a position of minimum radius. In a 12-1/4 in (311 mm) hole, the diameter of the tool varies when measured at the position of the fins from 11-3/4 in (298 mm) to 13-3/16 in (335 mm). Power from the electronics and the magnetic valves is supplied either by high temperature batteries (180° C) or a generator. The entire VDS was designed to operate at temperatures up to 200° C. To control the operations, the inclination is measured together with the operating parameters such as temperature, voltage and system pressures and the data transmitted through the mud column to surface by a mud pulser. In the KTB deep borehole, in the first 4000 m, with a few exceptions, the inclination of the wellbore was maintained within 1° (Engeser, 1996). This impressive control of verticality was continued within similar limits or 0.5° to 1° to about 7500 m when the temperature limits of the tool prevented further use. From 7500 m to TD at 9101 m, the trajectory deviated to the north east with inclinations up to 21° (Rischmuller, 1993).

4.3 COMMENT ON ENGINEERING AND COSTS

4.3.1 Drilling

The original concept and comments for deep disposal discussed in Juhlin and Sandstedt (1989) are for the most part still valid. The trade off between depth and diameter of the borehole is still a key issue. The experience of deep drilling in granites in Sweden has demonstrated that depths of 4000 m can be achieved without too much adverse influence from excessive hole stress breakout. The good experience of VDS on the KTB project in Germany improves the probability of successfully constructing 4000 m deep holes with diameters that are useable for waste disposal. To use the VDS in this context, consideration may have to be given to drilling a pilot hole with the VDS in say a 12-1/4 in (311 mm) hole size then opening the hole to the desired finished diameter using the pilot hole as a guide. Temperature limitations are not a problem as the temperature prognosis at 4 km is less than 100° C. The preferred option for a drilled diameter from the last study was 800 mm. It may be possible to increase this to 1000 mm especially if the disposal hole depth is at the lower end of the 2 km to 4 km range suggested previously. Any increase in bottom hole diameter will effect the upper diameters and casing dimensions.

Bit technology has improved over the years and so better bit life would be expected, although in the crystalline formations, the improvement may not be as significant as it has been in sedimentary formations.

New rig design and systems offer performance advantages not available in 1989 which would have an impact on overall costs, although unit costs have risen with more demand for deep drilling services.

4.3.2 Casing

The casing scheme is still the most challenging aspect of this concept. The casing design must be considered in conjunction with the sealing barriers, but the additional diameter that may be possible and the use of the vertical drilling technology to give a vertical hole with low tortuousity may make this task easier. The original concept of a high void ratio casing and the use of a high density bentonite is still a relatively simple and attractive way forward. However, material options and casing design concepts need further investigation.

New synthetic materials are now available which may have some application and this is another aspect which needs further consideration and research.

4.3.3 Coring, logging and testing

Since the drilling of the two deep boreholes in Sweden, there have been some good examples of the use of heavy duty, large diameter wireline coring systems in a variety of rock types including the crystalline basement. Over 25 000 m of high quality coring has been carried out for the investigation of radioactive waste sites in England, Scotland and France using a German system with 159 mm hole diameter and nominal 100 mm cores. Core recovery has been excellent averaging 99.5%.

If coring is required, it would be practical to core ahead in the pilot hole for short distances (say 50 m) using a still stabilised assembly so as not to create major adverse influences on the verticality control in the main drilling. Note that the VDS systems cannot be used with a coring system.

The range of wireline logging tools available has improved and more and more tools are available in smaller diameters.

Over the last few years, testing programmes have been developed and implemented very successfully to determine the hydrogeological characteristics of a range of rock types being considered for waste disposal. Testing has included the use of the coiled tubing systems. A major programme in the UK involving a comprehensive range of quality, low flow testing in deep boreholes to 2000 m and associated long term monitoring has been carried out over the last seven years. This included long term monitoring of pore pressures with the ability of sampling fluids in multiple zones using the Canadian Westbay system. The equipment has been developed to a high level of sophistication and installed in some modest depth boreholes (up to 1000 m, but still a world record) with up to 35 packed off sections monitored in real time simultaneously in one borehole (Eldred et al., 1995a; Eldred et al., 1995b).

The present system components are made from uPVC, but with stainless steels for the main load bearing string, the system could be developed further for deeper deployment.

This type of monitoring system has a place in the overall scheme of deep disposal concepts for providing the necessary long term monitoring control and for early assessment of flow and pressure data.

4.3.4 Sealing

No new experience can be offered with respect to the completion fluid design, deployment mud or sealing, but all these need to be reviewed in some detail if a pilot program is envisioned.

4.3.5 Time schedules

The time schedules and associated costs provided in 1989 may be somewhat conservative taking into account the potential from new rig design and better drilling equipment.

4.3.6 Risks

The risks discussed in Juhlin and Sandstedt (1989) remain the same. In the intervening years, there have been general improvements in drilling equipment design, drilling fluids, understanding of stress related drilling problems and directional control which, assuming a program is well engineered and planned, would broadly reduce the risks as they were envisioned in 1989. However, the unique nature of the proposal of deep disposal and the engineering requirements that are necessary, particularly the casing and sealing arrangements, still introduces risks which are difficult to quantify.

5 PLATE TECTONICS AND OROGENY

The continental crust of the Earth has a complex geological record of successive orogenic events. The theory of plate tectonics and the concept of orogeny is briefly presented here as a platform for the description of the geology at the drill sites and as a foundation for the description of the composition, structure and evolution of the continental crust. On a global scale, the outermost part of the Earth consists of 50 to 200 km thick rigid material known as the lithosphere which includes both the crust and upper mantle (Figure 5-1). Below the lithosphere lies the more plastic asthenosphere which is on the order of 100 to 300 km thick (e.g. Park, 1988; Blundell et al., 1992). Within the plate tectonic framework, the lithosphere, at present, can be divided into six major and a number of smaller plates that move relative to one another. Tectonic, magmatic and seismic activity is generally most intense at the plate boundaries. Most plates consist of two regions (Figure 5-1); an oceanic one with a thin basaltic crust and a continental one with a thicker granitoid crust. The lower density of the latter makes it positively buoyant and, thereby, impossible to subduct at destructive plate margins (see below).

The boundaries of the lithospheric plates are of three main types; (i) constructive, (ii) destructive, and (iii) conservative, which are seismically, tectonically, and volcanically active. However, there exist broad belts where the boundaries are not well defined and the effects of plate interactions are not clear. These areas may be denoted as plate boundary zones (Koius and Tilling, 1996).

It should be noted that at continental margins, the transition zones from continental to oceanic lithosphere, may or may not correspond with lithospheric plate boundaries. Those that do, such as the western margin of the American continents, are termed active margins. Those continental margins that lie within lithospheric plates, like the Atlantic margins of Europe and Africa, are termed passive margins (see Figures 5-1 to 5-3). These areas are lacking magmatism and are characterised by mature continental shelf sediments such as shelf sand and carbonate banks that are derived from the nearby continent.

5.1 DIVERGENT PLATE BOUNDARIES

Divergent boundaries are constructive since formation of new oceanic lithosphere occurs between the diverging plates along the oceanic ridges. Within these ridges, upwelling partially melted asthenospheric material produces basaltic magma which continuously forms new oceanic crust simultaneously with the formation of new underlying mantle lithosphere by cooling of the asthenospheric material as it is carried laterally away from the hotter ridge axis (Figure 5-1). The oceanic basalts are overlain by progressively thicker and older pelagic sediment away from the ridge axis. Ultimately, the oceanic lithosphere is consumed into the Earth at destructive plate boundaries.

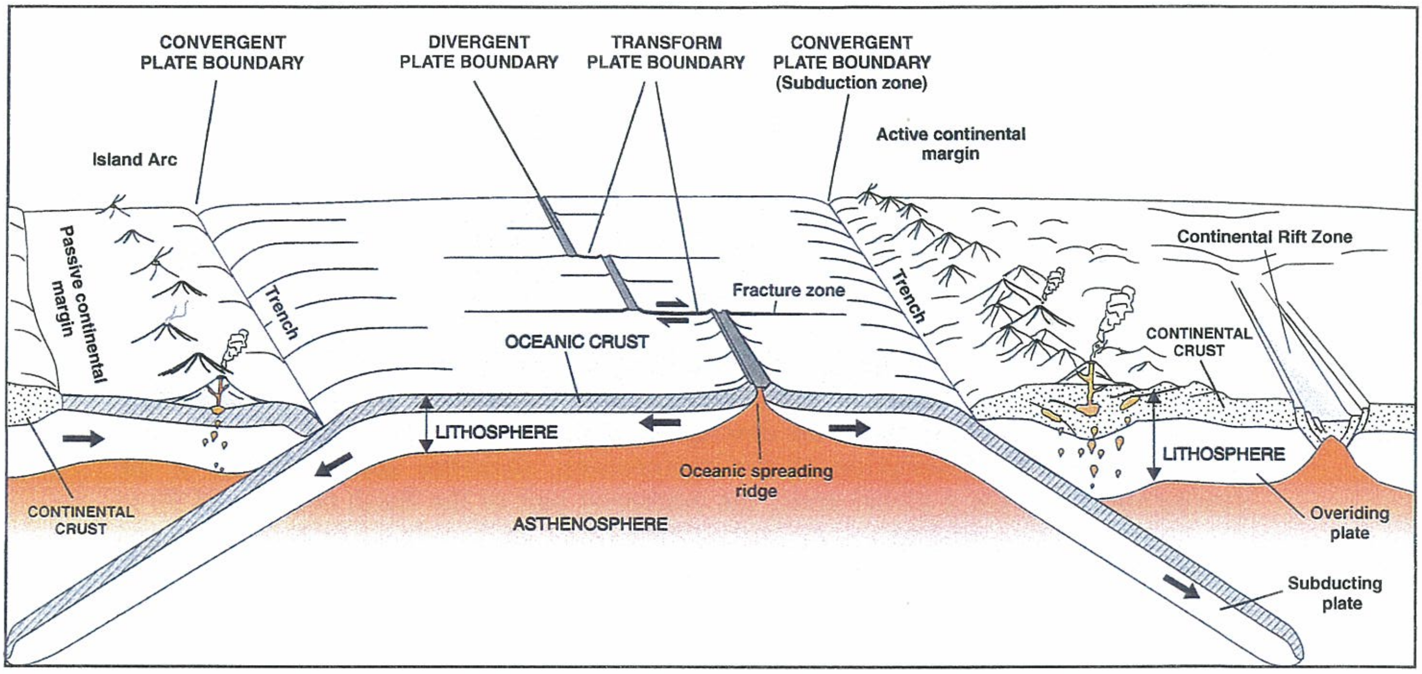


Figure 5-1. The plate tectonic model and the three major types of plate boundaries.

Continental rifting and the associated volcanism (e.g. the East African Rift Valley and Rhine graben) are considered to represent incipient constructive boundaries (continental rift zones, see Figure 5-1). These areas may eventually split up and result in the formation of new oceanic lithosphere between the diverging plates. In the initial stage these continental rifts become filled with fluvial (stream) and lacustrine (lake) deposits eroded from the adjacent faulted basin margins (Selly, 1976). Igneous activity produces lavas and volcaniclastic detritus which form layers and intercalations in the basin deposits. Basaltic rocks predominate, however acid rhyolitic volcanics occur also in the rift zones resulting in bimodal volcanic sequences (Wilson, 1989).

5.2 CONVERGENT PLATE BOUNDARIES

Convergent boundaries are formed where plates are destroyed. There are two basic types of convergent boundaries at present, (i) subduction zones and (ii) continental collision zones with a spectrum of transitional types between these two end members.

Subduction zones are plate boundaries where old (mean age 100 Ma), cool (negatively buoyant), oceanic lithosphere is destroyed by sinking into the asthenosphere and/or mesosphere (Davies, 1992). The subduction may take place below another oceanic plate or it may occur below adjoining continental lithosphere (i.e. the west coast of South America). The former results in a volcanic island arc above the subducting plate (Figure 5-1). The latter results in active continental margins, which are mountain belts capped with large volcanos (Figure 5-1).

Subduction zones are characterized by active volcanos producing fractionated volcanics from basalt to rhyolite, but also (in mature thickened island arcs and in active continental margins) deep seated plutonism forming granitoid batholiths.

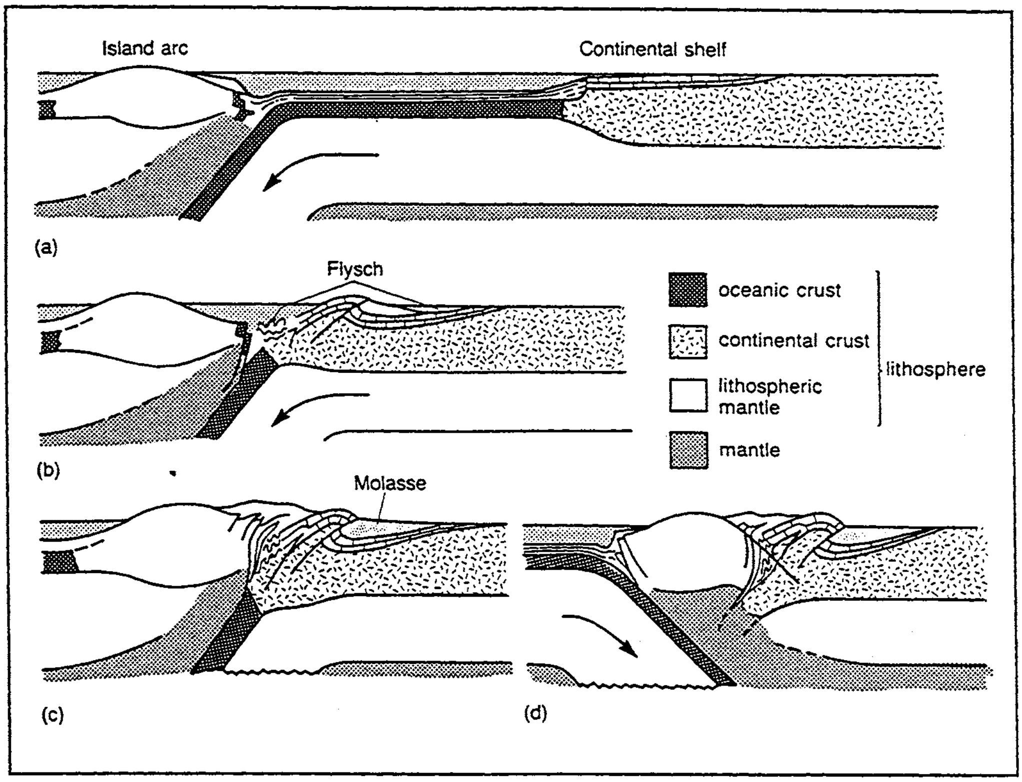


Figure 5-2. Tectonic facies. Cross-section of a subduction zone with an island arc, and a later collision event with a passive continental margin. Renewed subduction changes polarity after the collision. The magmatic activity in the mobile belt is not shown. From Dewey and Bird (1970) in Kearey and Vine (1990).

In the troughs (geosynclines) adjacent to the island arcs the deposition products are mainly juvenile. These syn-orogenic, immature terrigenous sediments, often with significant volcaniclastics and volcanogenic sediments form the flysch facies (Figure 5-2b) in active geosynclinal troughs. Later, during the late- and post-orogenic evolution of the subduction zone, weathering and extensive erosion of the orogenic mountain belt produces molasse sediments (Figure 5-2c; Selly, 1976). This partly marine, partly continental or deltaic sedimentary facies consists largely of coarse terrigeneous clastic material with abundant conglomerates, few shales and negligible limestones.

Thrust slices of oceanic crust carrying cherts and shales, together with upper mantle peridotites, may be scraped off or obducted during subduction and deposited along the trench slope of the overriding plate. These eventually slide down into the trench as "melanges" and mix with clastic flysch sediments to produce a thick wedge of sediments along the trench. Rifting may occur within the arcs, and back- or intra-arc marginal basins are formed, where new oceanic crust may be generated.

Figure 5-3 schematically demonstrates the effects of telescoping an active continental margin containing subduction tectonics against a passive continental margin. Considerably more complex collision zones exist. For example, the Caledonides, Alpine and Himalayan chains show evidence of several ancient subduction zones and island arcs which have now coalesced.

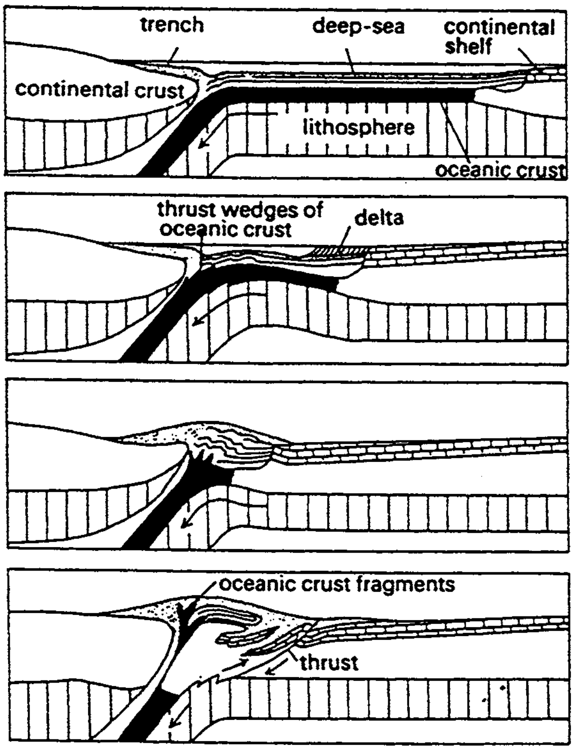


Figure 5-3. Schematic illustration of the stages in the transformation of a subduction zone to a continental collision zone by the destruction of the intervening ocean (the magmatic processes are not shown). After Dewey and Bird (1970) in Park (1988).

A full scale continental collision deforms all micro-continents, arcs and basins which may have existed in between. The collision event is dominated by deformation of the rocks involved, and the crust becomes shortened and thickened. The deformation sequence may include thrusting of rock slices on top of each other, movement of rock masses from the collision front by large strike slip faults, folding and shearing. An old plate border can sometimes be traced as a linear feature, known as a suture, and be distinguished by heterogeneous geological terrains including obducted ophiolites (oceanic crustal fragments).

The continental collision is normally followed by a regional metamorphic event, due to increased temperature in the thickened crust; uplift of the deformed sequences and erosion. Melting occurs towards the base of the thickened crust, forming migmatites and granitic magmas that invade the overlying crust. These granites differ in composition from the granites formed in volcanic arc environments (e.g. their high U and Th content). Erosional material from the mountainous areas is deposited in the continental basins in sedimentary sequences known as molasse (Figure 5-2). In a general sense, a continental collision corresponds to the traditional concept of orogeny as defined below.

5.3 TRANSFORM PLATE BOUNDARIES

Transform boundaries are composed of large, steep faults with a strike slip sense of displacement (transform faults; Figure 5-1). These faults connect two divergent plates. No creation or destruction of the lithosphere occurs along these plate boundaries. These prominent features commonly occur as parallel sets of faults offsetting the ocean ridges. The divergent movement away from the ridge axis is transformed to a dextral, strike slip motion along such transform faults. These plate boundaries are particularly abundant in the oceans but may occur on land like the Anatolian transform fault in Turkey, the Alpine fault in New Zealand, and the San Andreas Fault in western USA.

5.4 MOBILE BELTS AND OROGENIC BELTS/OROGENS

Present, and ancient, orogenic activity on the Earth principally occurs and occurred along converging plate boundaries as described above. The interior of the continental lithospheric plates represents stable areas called cratons and the unstable zones at the boundaries where the plates collide are called mobile belts.

Orogeny is defined as the process by which structures within mobile belts and mountainous areas form. These include thrusting, folding, and faulting in the outer and upper crustal layers and plastic folding, metamorphism and plutonism in the inner and deeper layers (Bates and Jackson, 1984). When orogenic belts are young they form pronounced mountain ranges (e.g. the Alpine-Himalayan belt). Ancient stabilised mobile belts are called orogenic belts or orogens (i.e. regions affected by the orogenic process).

In these mobile belts rocks and sediments from different tectonic terrains, such as slices of oceanic crust, island arc and active continental margin volcanic and plutonic rocks, oceanic sediments (e.g. shale and chert), piles of passive continental margin sediments (e.g. shelf sand and carbonates), piles of syn-orogenic flysch and late orogenic molasse sediments, are telescoped and welded together forming highly complex geological provinces (Figure 5-3).

The craton consists of a platform of primarily undeformed flat-lying sedimentary cover lying on top of older (generally Precambrian age) complex crystalline basement. A large exposed area of this crystalline basement is termed a shield. The crust of these stable cratons is thus composed of worn-down remnants of older mobile belts.

The interior of continental lithospheric plates are normally devoid of orogenic activity. Intrusion of basaltic magma below the crust (magmatic underplating) may induce melting and formation of granitoid magmas in the lower crust. The magmatism within continents includes specific types of granites, mixed massifs of mafic-felsic composition, very large mafic layered intrusions, and kimberlites. Sediments deposited within continents are mainly immature sandstones, conglomerates and related more fine-grained clastic rocks. Compared to marine sediments, the sedimentation rate is much lower and the regional extent much less.

5.5 THE CONTINENTAL CRUST

The continental crust (the outer felsic part of the continental lithosphere), including continental shelves and slopes, makes up about 40 % of the surface area of the Earth. The thickness of the continental crust ranges from some 20 km to as much as 60 km below the presently active orogens (e.g. Blundell et al., 1992). The seismic velocity discontinuity that separates the crust from the mantle is known as the Mohorovicic discontinuity (Moho). This physical transition zone generally corresponds with the petrological change between basalt in the crust to peridotite in the mantle.

The composition, structure, and thickness of the continental crust is, as can be expected from its long geological history, highly variable. As described above, the crust is made up of highly different lithotectonic terrains amalgamated in mobile belts at destructive plate boundaries. Younger orogenic events commonly reactivate older crustal terrains and thereby further enhance the complexity of the continental crust.

The oceanic crust, on the other hand, is less complex and has an average thickness of only 7 km (e.g. Davies, 1992). It is principally composed of basaltic lava, basaltic dike complexes and gabbros formed at the oceanic ridges. The ocean floor is, as it spreads out from the oceanic ridges, continuously covered by gradually thicker pelagic sediments, such as chert, maganiferrous shale and ultimately, at destructive plate margins, flysch sediments (e.g. Selly, 1976).

Although a highly simplistic model, the continental crust is generally divided, at the Conrad discontinuity at about 10-20 km depth, into an upper and a lower part (Figure 5-4). The discontinuity appears to be present in some areas, but not in others, which exemplifies the structural and compositional complexity of the crust (e.g. Smithson, 1978; Taylor and McLennan, 1985).

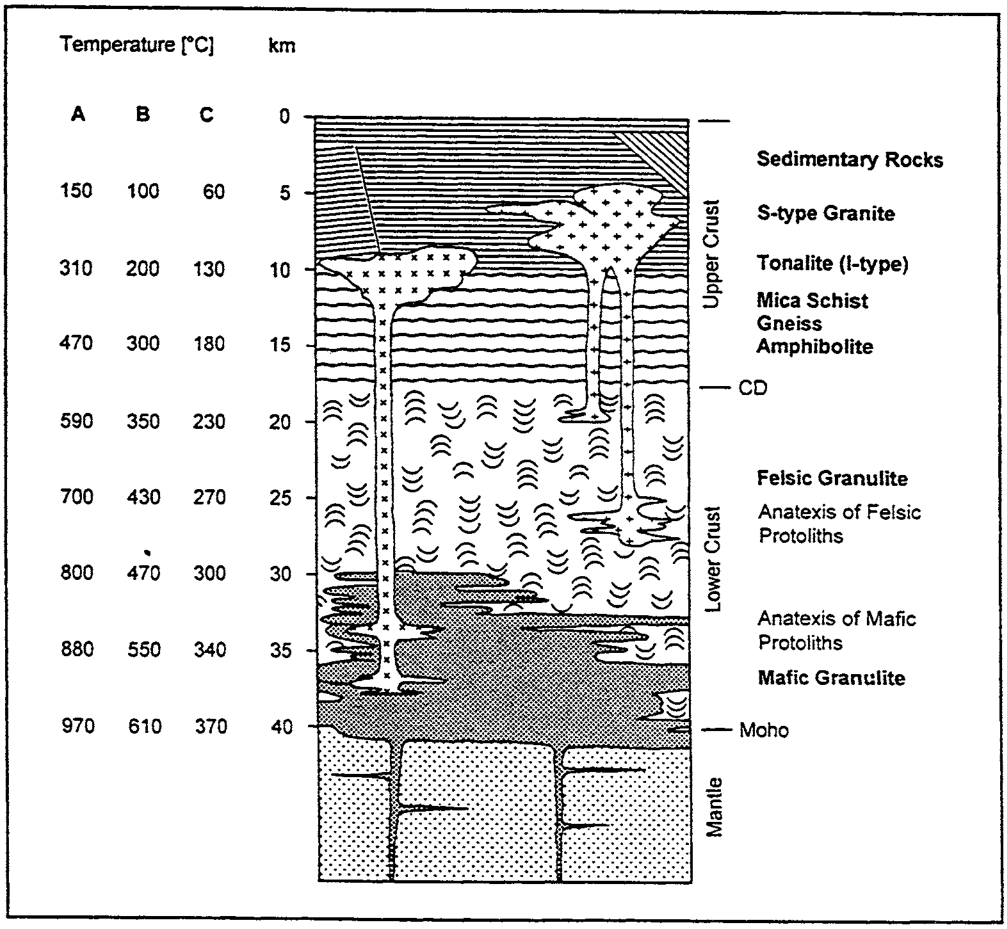


Figure 5-4. Simplified cross section of the continental crust and change of temperature with depth (from Johannes and Holtz, 1996). CD = Conrad discontinuity. Temperature conditions for A = orogenic crust, B = young crust, and C = stable shield crust. Note that the indicated temperature at 5 km is somewhat lower than what is expected in the Swedish part of the Baltic Shield.

Figure 5-4 shows that the temperature conditions within the crust in active orogenic belts is highly disturbed. Following orogenic crustal thickening, the intrusion of magmas, fluid flow, and late-orogenic exhumation generally results in considerably higher temperatures in the crust compared to a stable cratonic environment.

Data about the composition of the lower crust comes principally from two sources: high-grade metamorphic (granulite facies) terrains that are now exposed by tectonics and/or erosion at the surface of the Earth and granulite facies xenoliths that are carried to the surface in volcanic conduits and dikes (Clark, 1992). In general, the lower crust is interpreted to consist of felsic and mafic granulites (Figure 5-4).

The average composition of the upper crust is well established as being of granodioritic composition (Smithson, 1978; Taylor and McLennan, 1985). It consists of sedimentary rocks, metamorphic rocks, and magmatic rocks in the rough proportions of 1:4:4 (Johannes and Holtz, 1996). The shields are, as per definition, basically composed of granitic intrusives along with metamorphic rocks (granitic gneisses, meta-greywackes, and metapelites).

The granitic intrusions show great variation in their three-dimensional shape and size. Some are concordant small dikes measuring a few metres wide while others are discordant batholiths hundreds of kilometres wide. The primary shape of the intrusions is related to the regional stress field and rheology of the crust and intruding magma (Castro, 1987; Hutton, 1988). The degree of post-magmatic (or post-emplacement) deformation is principally related to the age of the granite in relation to the orogenic development.

Formation of the granitic crust is generally considered to involve three steps (Buddington, 1959; Clark, 1992; Johannes and Holtz, 1996; Wyllie, 1977). First the formation of mafic rocks derived from the mantle (at e.g. oceanic ridges and island arcs). The second step (shown in the left hand side of Figure 5-4) involves partial melting of this rock and formation of tonalites in the early Archean crust and mafic granulitic residues. The third step (shown in the right hand side of Figure 5-4) consists of partial melting of the tonalitic crust and overlying sediments and volcanics, resulting in more felsic granites (at e.g. continental collisional orogens) and a felsic granulitic residue depleted in granite components.

5.6 THE GEOLOGICAL TIME SCALE

An important aspect of geology is time (Figure 5-5). From the creation of the planet Earth c. 4.6 Ga the processes that have produced the rocks present today have changed and evolved. The chronological development of rocks may be studied with two different approaches; relative relationships between two adjacent rock types (e.g. field work), and studies of the time-dependent radioactive isotopes (absolute age dating). From these parameters the relations of rocks within one orogeny may be interpreted and the orogeny be placed within a time column. With the introduction of life another aspect of the geological evolution is to be added. From c. Cambrian (0.57 Ga; Figure 5-5), abundant fossils of marine life may be studied in well preserved sediments. These fossils are important time markers, not just because they are restricted to particular time intervals, but also give information on depositional environment. The ages of the time scale is calibrated with fossils at type localities. In the Precambrian, the life forms were very scarce and primitive, probably restricted to single-cell algae.

Orogeny	Eon	Era	Period	Million years
Alpine	Phanerozoic	Cenozoic	Quaternary	2
			Tertiary	65
		Mesozoic	Cretaceous	145
			Jurassic	210
			Triassic	245
		Palaeozoic	Permian	290
Variscan			Carboniferous	360
Caledonian			Devonian	400
			Silurian	440
			Ordovician	510
			Cambrian	570
	Proterozoic		Vendian	700
			Neo-proterozoic	1000
Sveconorwegian			Riphean Meso-proterozoic	1600
Gothian Svecokarelian			Palaeo-proterozoic	2500
Archaean orogenies	Archaeozoic			

Figure 5-5. Simplified time scale and major orogenic events in Europe. Length of Phanerozoic eras and periods are shown to scale.

6 GEOLOGICAL UNITS OF EUROPE

The bedrock geology of Europe has been divided into a number of geographical sectors based upon the age and tectonic history of the rocks within each sector. The oldest rocks are found in two areas; the Baltic shield, exposed in the northern part of Europe, and the Ukrainian shield (Figure 6-1). Shield areas are defined as large regions of exposed basement rocks of Precambrian age, surrounded by sedimentary rocks. The Baltic and Ukrainian shields are covered by Phanerozoic (younger than 0.57 Ga) sedimentary rocks which form the East European Platform (the shield and platform together constitute the East European Craton). The Tornquist line, or Transeuropean fault system, is generally considered to represent the western boundary of the East European Platform (Figure 6-1).

In Europe, three Phanerozoic orogenic events are superimposed on the older Precambrian orogenic units and consist of 1) the Caledonian orogen with younger sedimentary cover on the British isles and northern Europe, 2) the Variscan and Uralide orogens exposed in a number of massifs in SW and central Europe and in the Urals, and 3) the Alpine orogen, which forms pronounced mountain belts in southern Europe and further east, and includes some very young sedimentary cover adjacent to the orogenic belts.

6.1 THE PRECAMBRIAN SHIELDS

The Baltic or Fennoscandian shield (Figure 6-2) consists of Precambrian rocks ranging in age from Early Archean (3.0-3.5 Ga) on the Kola peninsula and Karelia to Neoproterozoic in the SW part of the Shield. These shield rocks are mainly crystalline and of granitic composition, deformed and metamorphosed during Precambrian orogenies. The shield is covered by Palaeozoic and Mesozoic sediments on a pronounced erosional disconformity, the sub-Cambrian peneplain, (Lidmar-Bergström, 1994). Younger magmatic activity is mainly concentrated to the Palaeozoic alkaline massifs on the Kola peninsula and in the Oslo graben. Crustal thickness is interpreted from seismic investigations to be within a range from c. 35 km in SW Scandinavia, to more than 60 km where it is thickest in eastern Finland (Korja et al., 1993). The lithospheric thickness varies from ca. 110 km in the west to over 200 km below the Bothnian Bay (Blundell et al., 1992). To the south, the Ukrainian Shield is exposed and forms part of the same craton as the Baltic Shield (Gorbatschev and Bogdanova, 1993). However, due to the overburden, the details of how the two shields are related is not known.

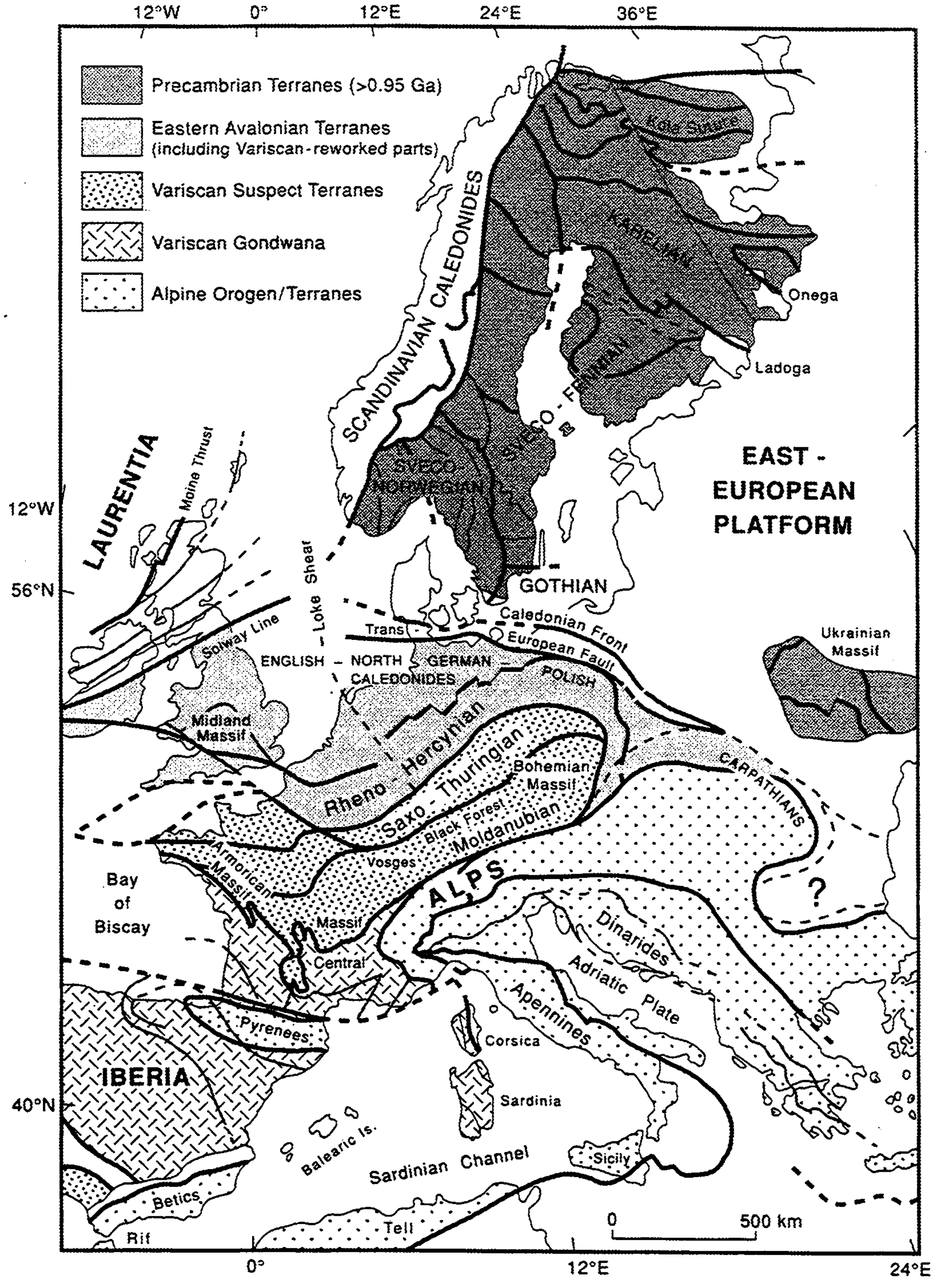


Figure 6-1. Tectonic subdivision of the Precambrian shield areas and the Caledonian and Variscan orogenies in Europe. From Berthelsen (1992).

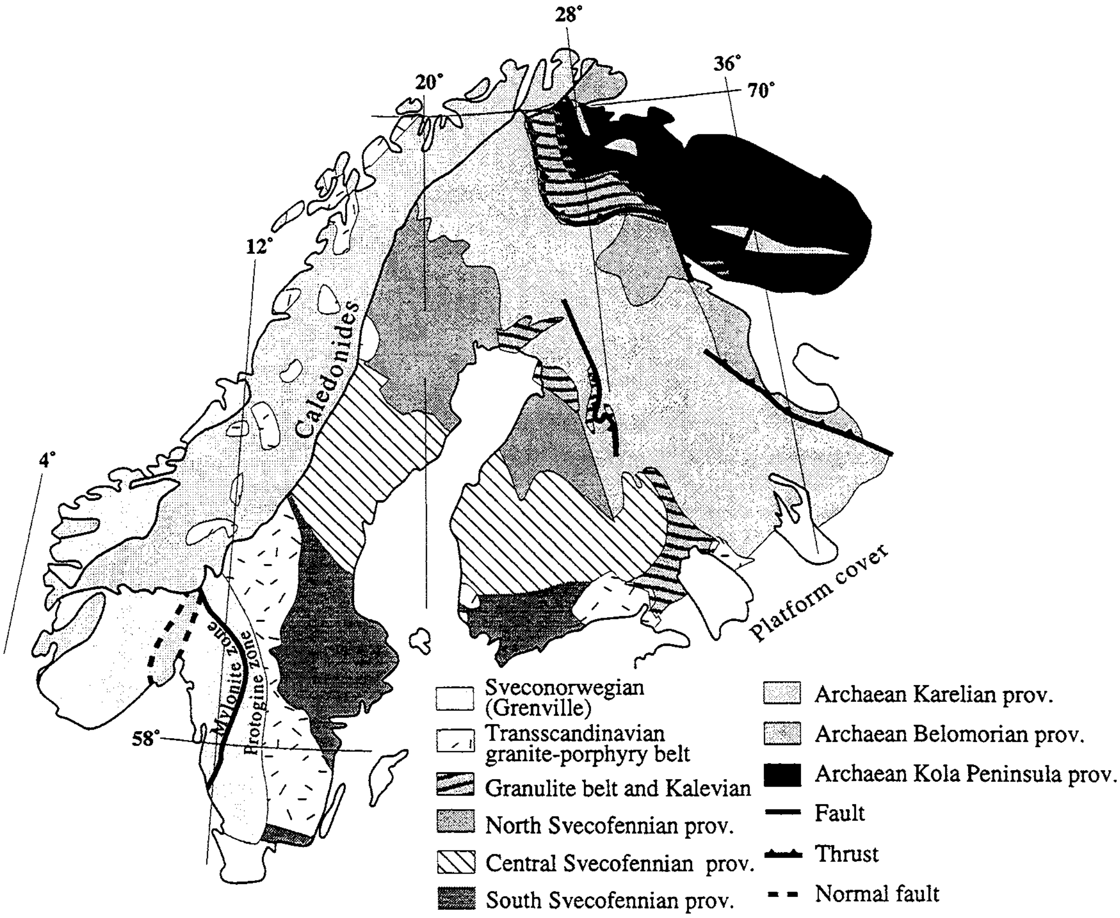


Figure 6-2. Geological units of the Baltic Shield. Map from Weihed et al. (1992).

The Ukrainian shield can be divided into five Precambrian blocks, separated by approx. N-S trending faults. A two-fold division has been suggested (Gaal and Kazansky, 1986), where the two eastern blocks are Archean crust which were cratonised at c. 2.7-2.5 Ga and the three western blocks are composed of Proterozoic crust. The Proterozoic units are composed of medium grade metamorphic continental basin rocks of the Krivoy Rog Group, shelf-deposited rocks and metapelites of the Ingulo-Ingulets and Teterev Groups, high-grade metamorphic supracrustal and granitic rocks and granitoid batholiths. A number of very large Rapakivi intrusions with a c. 1.7 Ga age (Gorbatschev and Bogdanova, 1993) occur within the shield. The Ukrainian shield is truncated to the north by the Palaeozoic NW-SE trending Dneipr-Donets aulacogen and the northwards continuation of the shield is found in the Voronezh uplift 200 km further to the north.

6.2 THE CALEDONIAN OROGEN

The rocks of the Caledonian orogen are exposed in Scandinavia and on the British isles. Related rocks that formed within the same orogeny, are exposed on Greenland, in the Appalachian mountains, and on Newfoundland.

The European and North American continents formed one single continental mass from the Sveconorwegian/Grenvillian orogeny in the late Precambrian (Gower, 1985), until the youngest Precambrian, c. 0.7 Ga, when the two continents were rifted apart, forming the Iapetus ocean. Along the Baltica margin a subduction complex with a volcanic arc and a succession of arc-continent collisions occurred in Late Cambrian-Early Ordovician, the Finnmarkian orogenic episode (Stephens and Gee, 1989). In the Ordovician, subduction zones also formed along the margin of the American continent. The Caledonian orogeny culminated in Silurian and Devonian times (c. 420–380 Ma, see Figure 5-5), when the Iapetus Ocean closed and Baltica and the North American (Laurentia) continents collided and amalgamated to form part of the super-continent Pangaea. In Scandinavia, the Caledonide rocks are characterised by nappes, large horizontal thrust slices of rock, transported from west to east over the Baltic shield basement. The nappes consist mainly of Palaeozoic sedimentary and igneous rocks and slices of Precambrian basement.

South of the amalgamated Laurentia-Baltica continent, another microcontinent called Avalonia drifted northward and docked with the newly formed plate. The Laurentia-Baltica/Avalonia suture is expressed as a series of E-W trending faults (e.g. Trans-European fault, Figures 3-3 and 6-1). The Avalonian fold belt may also be called the Middle European Caledonides and occupies most of the basement in the central part of the British Isles, northern Germany and Poland. The Avalonian belt is covered by a thick Mesozoic sedimentary package and exposures are rare.

An important point is that the present rugged topography of the Scandinavian Caledonides is a product erosion over the last 400 million years and more recent uplift/tilting tectonics due to the Mesozoic Atlantic rifting.

The nappes of the Scandinavian Caledonides contain fragments of rock units from different tectonic settings, which formed west of the Baltica continent (Stephens and Gee, 1989). The lowest tectonostratigraphic nappes (Lower and Middle Allochton) were formed at the continental margin of Baltica, i.e., slices of Precambrian basement rocks and Cambrian/Ordovician cover rocks. Included are also the Seve nappes, metasediments and amphibolites metamorphosed during the Finnmarkian orogeny. The upper tectonostratigraphic nappes (Upper and Uppermost Allochton) contain fragments of the Iapetus ocean floor, volcanics and sediments from volcanic arc environments, and metamorphosed sedimentary rocks from the Iapetus oceanic environment. One nappe from the Uppermost Allochton includes abundant granitoids and metamorphosed sediments, and it is interpreted to be a piece of Laurentia.

6.3 THE VARISCAN (HERCYNIAN) OROGEN

Rocks subjected to the continental Variscan collision are exposed on the Iberian peninsula, and in a number of massifs in continental Europe (Figures 3-3 and 6-1). Otherwise they have been covered by younger sediments. Variscan deformation is superimposed on the southernmost part of the Caledonian rocks and also includes rocks from the southern large Gondwana continent. The collisional events occurred in Carboniferous times, at c. 350-300 Ma, and the Variscan orogeny closely followed the Caledonian orogeny temporally.

The Variscan orogen can be divided into three main structural elements; the Rheno-Hercynian, the Saxo-Thuringian and the Moldanubian zones (Figure 6-1), which form elongated, arcuate E-W belts through Europe. The Variscan orogenic rocks are overprinted to the south by the Alpine orogeny, which also includes fragments of Variscan rocks.

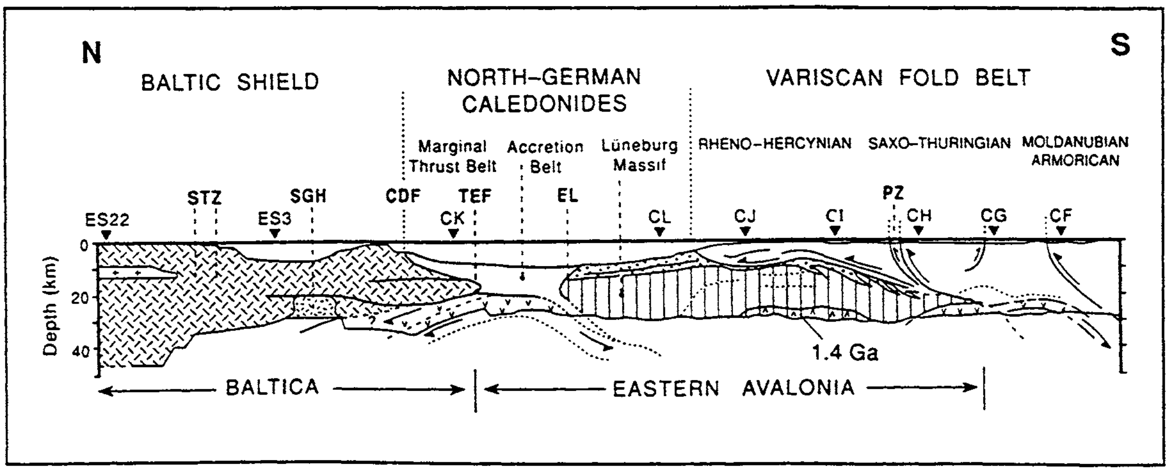


Figure 6-3. Crustal structure in Europe along the central part of the roughly N-S trending European Geo-Traverse (EGT). STZ= Tornquist zone, SGH=Silkeborg gravity high, CDF= Caledonian front, TEF=Trans-European fault, EL=Elbe line, PZ= northern phyllite zone. Epi-Cadomian cover is stippled. Underlying Cadomian and older crystallines of the Lüneburg massif have open vertical ruling. (from Blundell et al., 1992)

After the Caledonian orogenic events, the Laurentia-Baltica plate including the southern Avalonian microplate, formed a northern continent. To the south, the large Gondwana continent was moving northwards. A number of narrow ocean basins formed along the northern margin of Gondwana. The northernmost Rheno-Hercynian basin was filled by thick Devonian sediments whose source was the northern Laurentia-Baltica continent. The ocean floor was subducted southwards and a volcanic arc, present today as the Mid-German Crystalline High (MGCH), was formed and constitutes the northern part of the Saxo-Thuringian zone. Finally, this volcanic arc terrain collided with the Avalonian terrain, forming a suture with ophiolite complexes (the Lizard complex, SW England and the Harz area, Germany) along this former plate margin. This contact between the Rheno-Hercynian and Saxo-Thuringian is a thrust with tectonic transport from south to north (Figure 6-3).

In the southern part of the Saxo-Thuringian zone, sedimentation continued until the Gondwana continent arrived from the south and closed the basin south of the eroded MGCH volcanic arc. The contact zone to the Gondwana-derived Moldanubian zone includes a characteristic high grade metamorphic zone containing eclogites at the front.

A phase of post-collisional activity ended the Variscan orogeny with large-scale crustal stacking, low-P metamorphism, intrusion of late to post-orogenic granites.

6.4 THE URALIDE OROGEN

The Ural mountain chain forms a c. 2500 km long, and 400–450 km wide fold belt running in the N-S direction. It originated by a continental collision of the East European Craton and the continental Kazachstan plate, approximately synchronous with the Hercynian-Variscan folding of western Europe at c. 320-245 Ma (Edwards and Wasserburg, 1985). The mountain range was uplifted from marine to subaerial conditions at c. 290 Ma. The Ural belt may be divided into a number of structural units (or megazones, (Snyder et al., 1994)), emplaced as thrust sheets transported from east towards west over the margin of the East European Craton.

Continental break-up and formation of a Pre-Uralian ocean east of the East European Craton occurred in the Late Precambrian, followed by sedimentation at the new continental margin. Sedimentation, volcanic arc evolution, and minor microcontinent collisions occurred in several steps, until Devonian-Carboniferous times when the subduction was followed by a continental collision stage. A typical feature of the Ural fold belt is the presence of Silurian ophiolite complexes, emplaced by westward obduction of Uralian ocean floor. This stage (c. 400 Ma) coincides temporally with the first stage metamorphism and the formation of a suture zone, now associated with the Main Uralian Fault. Several rock units, especially ophiolites west of the Main Uralian Fault are found within more or less horizontal nappes (Zonenshain et al., 1984). Strong block faulting and uplift followed the thrust tectonics and exposed basement rocks. A late phase of regional metamorphism and granite intrusion occurred.

6.5 THE ALPINE OROGEN

Included into the Alpine orogeny are the Atlas mountains in north Africa, the Betics in southern Spain, the Pyrenees, the Apennines, the Alps, the Carpathians in eastern Europe, the Dinarides, the Balkanides and the Hellenides on the Balkan peninsula. The Caucasus mountain range between the Black and the Caspian Sea are also part of this orogeny. Alpine orogenic activity has been active for approximately 100 Ma, and two distinct episodes of mountain building events in central Europe may be outlined, one in the Cretaceous (Eo-Alpine), and the other in the Tertiary. Recent subduction with associated volcanism and back arc extension/rifting is still ongoing in the Mediterranean region. This is, for example, manifested by the active volcanism in southern Italy on the Lipari islands and on Sicily as well as on Santorini in the southern Aegean Sea (Figure 6-1),

By the Variscan orogeny, Europe and Africa were joined together in the supercontinent Pangaea. This stage was followed by separation of the two continents in the Jurassic and formation of the Mediterranean Sea. Several microplates with intervening basins existed between the two large continents, which rotated, grew or collided with each other, forming a complex mosaic of geological settings. The Mediterranean rifting is more or less synchronous with the Atlantic rifting and the separation of Europe/Africa from the Americas.

At the onset of the Alpine orogeny sedimentation patterns change from carbonate shelf assemblages, typical for the Mediterranean area to orogenic flysch type clastic sediments. As the basins were consumed, the microplates collided and formed thrust and fold belts. The Iberian plate was docked to the American plate for some time, but became decoupled and collided with Europe as the Pyrenees formed. The Turkish plate was transported westwards along prominent triangular shaped transform faults, due to the north directed movement of the Arabian plate. The Adriatic plate rotated anti-clockwise, closed the Piedmont basin, and initiated the typical arcuate Alpine mountain belt (see Figure 3-3). Back arc rifts are still being created, due to these complicated microplate movements, in the Tyrrhenian Sea. Extensive uplift of the orogenic belts superseded the tectonic movements. Sediments from the mountainous area were and are deposited in molasse basins around the Alps, for example the Po basin.

7 CRUSTAL STRUCTURE: BALTIC SHIELD

7.1 GEOLOGY OF THE BALTIC SHIELD

7.1.1 The Archaean Kola-Karelian terrain

The geology of the Kola peninsula (Figure 7-1), may be divided into a number of Archaean blocks separated by major NW trending strike-slip faults (Lanev et al., 1987). The rocks on the Kola peninsula are mainly gneisses of sedimentary origin and trondhjemitic gneisses. The Karelian terrain is composed of better preserved Archaean greenstone belts with volcanics and sediments, separated by higher grade metamorphosed tonalitic gneisses and migmatites. The Archaean basement was covered by several younger volcano-sedimentary units (Gaal & Gorbatschev, 1987); the Lapponian unit which resembles the Archaean greenstone belts, an important continental rifting unit at c. 2.5-2.4 Ga (Sumi-Sarolian), and a shelf deposition unit at 2.2-2.0 Ga (Jatulian). Collision tectonics amalgamated the Archaean blocks and their associated Proterozoic cover c. 2.0-1.9 Ga. The Lapland Granulite Belt was also formed during this event.

7.1.2 The Svecofennian terrain

The Svecofennian orogen is composed of a number of volcanic island arc, and associated sediment, and granitoid terrains formed in the time interval 2.0–1.75 Ga. It experienced metamorphism and crustal melting c. 1.82–1.78 Ga. This terrain is, according to e.g. Windley (1992), separated from the Archaean terrain by the Luleå-Kuopio zone which is interpreted to be an ancient collisional suture. At present, more correctly, the Svecokarelian orogen is used to denote the area affected by orogenic processes during the Palaeoproterozoic period. This implies that the entire northern part of Sweden belongs to the Svecokarelian orogen.

The major Transscandinavian Granite Porphyry Belt (TGPB), mainly composed of several generations of granitoid and dioritoid plutonics and felsic volcanics with ages in the interval 1.85–1.65 Ga (Person and Wikström, 1993), occupies the western margin of the Svecofennian crust. Anorogenic magmatic episodes include for example Rapakivi granites in southern Finland, and several dolerite dike swarms, the youngest being encountered at c. 900 Ma (Johansson and Johansson, 1990).

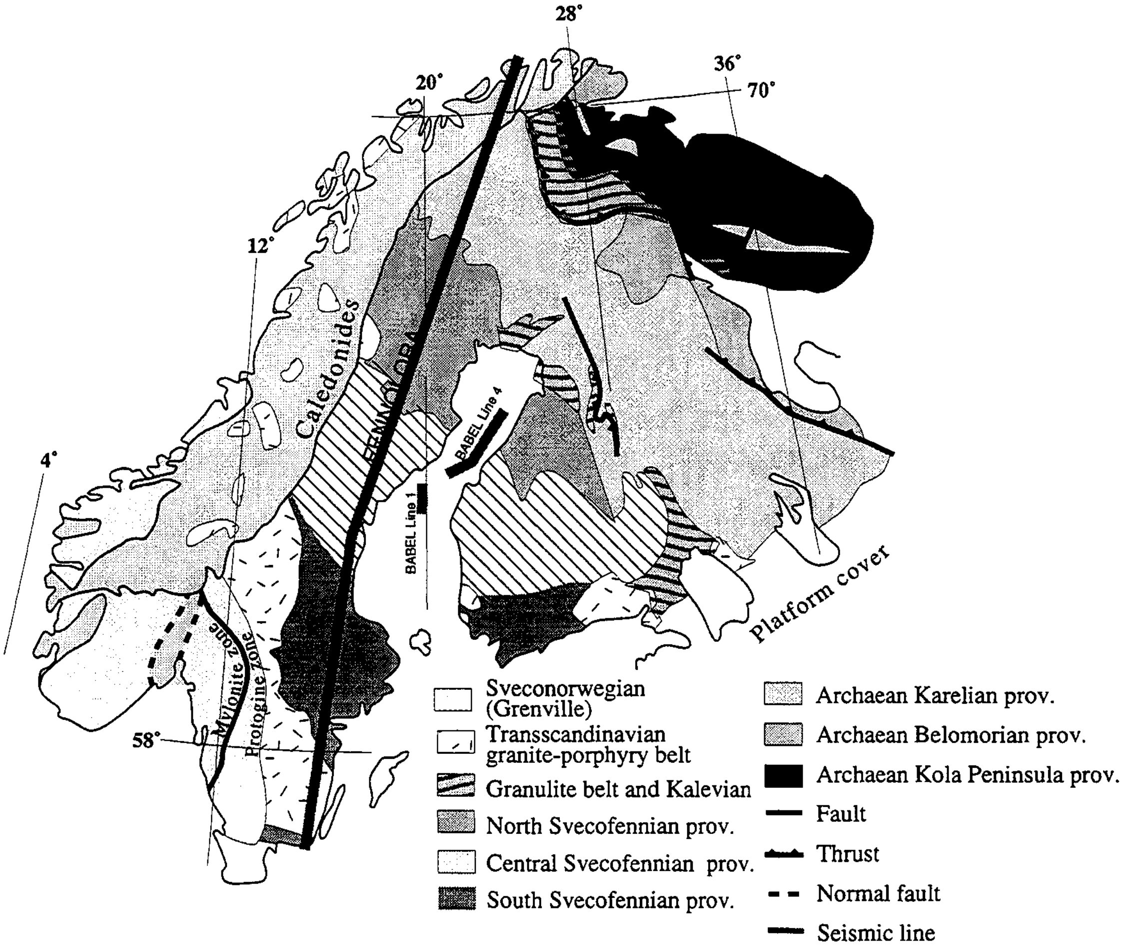


Figure 7-1. Geological units of the Baltic Shield and locations of the FENNOLORA profile (Figure 7-2) and seismic profiles BABEL Line 4 (Figure 7-3) and part of BABEL Line 1 (Figure 7-4). Map from Weihed et al. (1992).

7.1.3 The Gothian/Sveconorwegian terrain

The Sveconorwegian orogen is situated west of the TGPB (Figure 7-1). It consists mainly of high grade granitoid gneisses with some intercalated volcanic and sedimentary terrains. These rocks were principally formed during the Gothian orogeny at c. 1.6 Ga, which makes these rocks coeval or slightly younger than the rocks in the TGPB. Important approximately N-S trending fault zones traverse the Sveconorwegian orogen. The terrain experienced continent-continent collision at the end of the Sveconorwegian/Grenvillian orogeny at c. 1.1–1.0 Ga, which further added deformation and metamorphic complexity on the pre-existing Gothian orogen.

7.1.4 Plate tectonic aspects

The theory of plate tectonics (see chapter 5) explains satisfactorily not only crustal structures and evolution, but also the distribution and variation both of igneous and metamorphic activity, heat flow, and sedimentary facies. It also provides us with a regional system useful for stratigraphic and litho-tectonic subdivision of shield area rocks with the concept of mobile belts/orogens. Since the plate tectonic model developed primarily from observations on rocks of relatively recent age, Cambrian (0.57 Ga) and later, one may ask how far back in time did plate tectonic processes operate on the Earth? This question is highly relevant for the Baltic Shield since it is made up of rocks which are considerably older with primarily Proterozoic (c. 2.5-0.57 Ga) in the southern part and Archaean (> c. 2.5 Ga) in the north. The existence of c. 2.0 Ga old oceanic crust thrust onto land (ophiolites) in Canada (Hoffman, 1989) indicates that plate tectonics was active in the early Proterozoic. Results from the BABEL experiment (see next section) support the theory that a model with stable cratonic areas and mobile belts with orogenic activity can be extrapolated far back in Earth history.

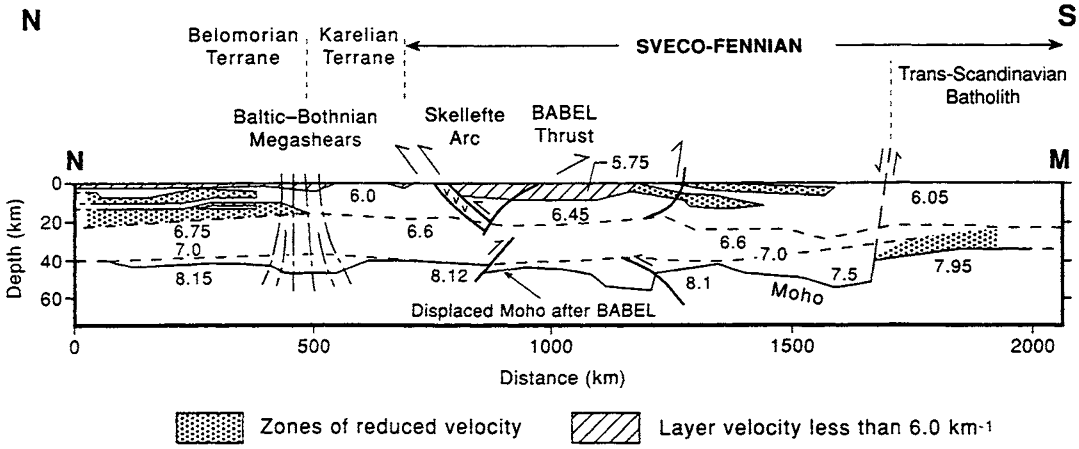
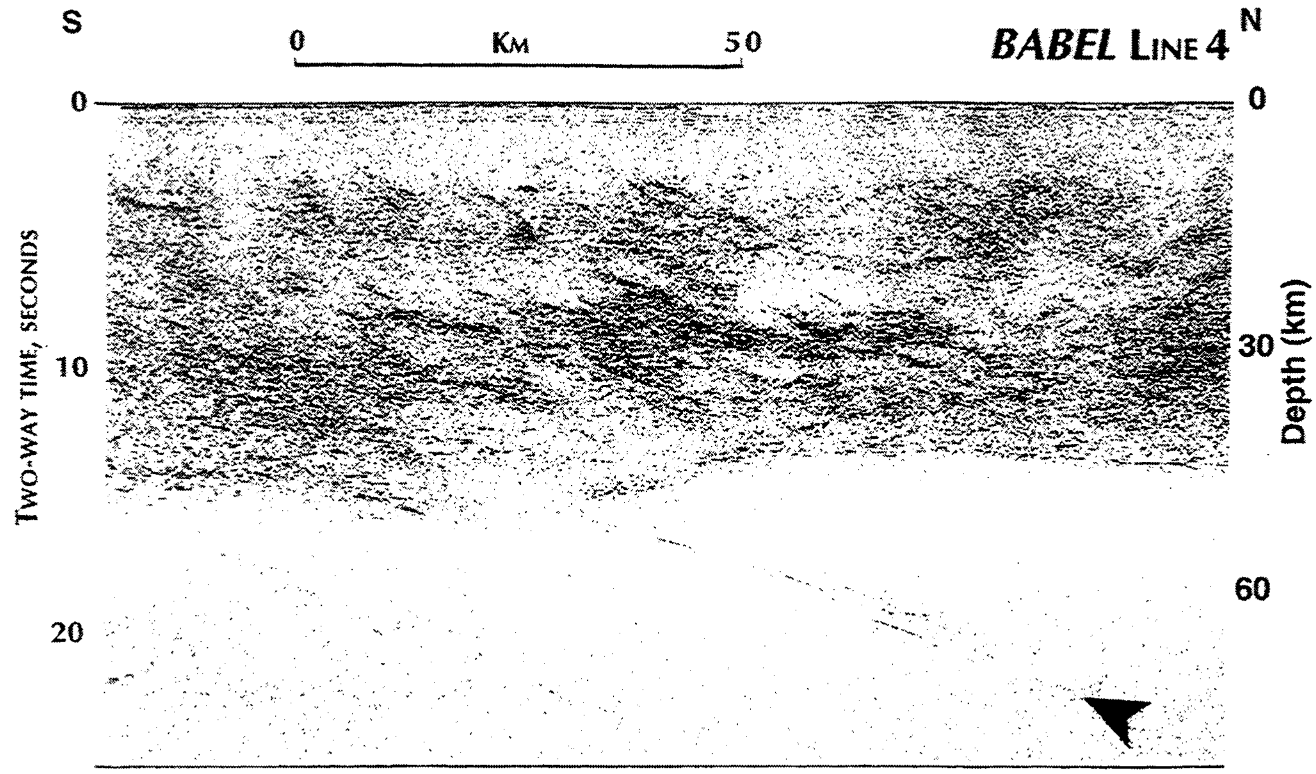


Figure 7-2. Crustal structure of the Baltic Shield along the FENNOLORA profile in Figure 7-1. (after Guggisberg et al., 1991; from Blundell et al., 1992).

The FENNOLORA long range seismic profile (Figures 7-1 and 7-2) shows the large scale present day P-wave velocity structure of the Baltic Shield (Guggisberg et al., 1991). This structure is the result of plate tectonics working over billions of years. The crust can be divided into two layers, an upper c. 20 km thick one with P-wave velocities of 6.0-6.4 km/s and a lower one with more variable thickness. Note that the FENNOLORA profile was designed to investigate the lower crust and upper mantle implying that any small scale lateral variation in the upper crust will not be observed. The lower crust has P-wave velocities of 6.55-6.7 km/s at its top which increase to 6.9-7.5 km/s at its base. The topography of the Moho varies rapidly. At c. km 1200 and km 1700, for example, there are offsets of about 10 km (Figure 7-2). Changes such as these are important since lithospheric strength is dependent on, among other factors, crustal thickness. A thicker crust implies a weaker lithosphere.

7.2 SEISMIC PROFILING RESULTS FROM BABEL

In 1989 2,268 km of near-vertical incidence reflection seismic data were acquired in the Baltic sea, the Bothnian Sea and the Gulf of Bothnia during the BABEL (**Ba**ltic and **B**othnian **E**choes from the **L**ithosphere) project. Figure 7-1 shows the location of those portions of the profiles reported on in this study. The main goal of the project was to study the crustal reflectivity of an ancient shield and compare it with the many



(a)

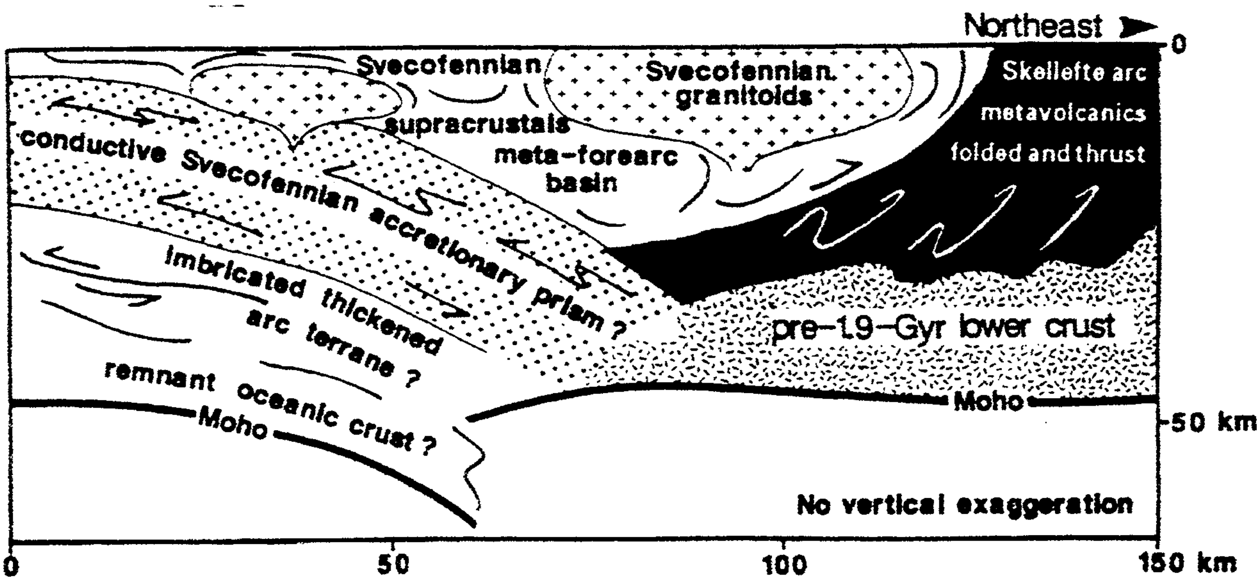


Figure 7-3. a) Reflection image obtained from BABEL Line 4. b) Interpretation of section. For location see Figure 7-1. Figures from Snyder (1991) and BABEL Working Group (1991a).

reflection seismic surveys from younger areas in order to gain a better understanding of crustal evolution. One of the results from the BABEL project was the observation of a deep crustal reflectivity pattern in the Gulf of Bothnia (Figure 7-3) similar to that observed below modern collisional features such as the Alps (BABEL Working Group, 1991a). The observation indicates that it is highly likely that plate tectonics was active throughout the Proterozoic in much the same way as we observe it today. This implies that we can use a uniformistic approach when interpreting and trying to understanding the crustal architecture of the Precambrian. However, it is still not clear if plate tectonics, as we know it, was active during the Archean.

Further south, in the Bothnian Sea, several sub-horizontal reflectors were observed in the upper 4 seconds of two-way-traveltime (c. 12 km) (Figure 7-4). These reflectors are of a similar nature to those observed in the Siljan Ring area (Juhlin and Pedersen, 1993) and are interpreted to originate from dolerite sills (BABEL Working Group, 1991b). The discovery of the dolerite sills in the Siljan Ring area and under the Bothnian Sea indicates that sub-horizontal structures may be significantly more widespread in the upper crust of the Baltic Shield than previously believed.

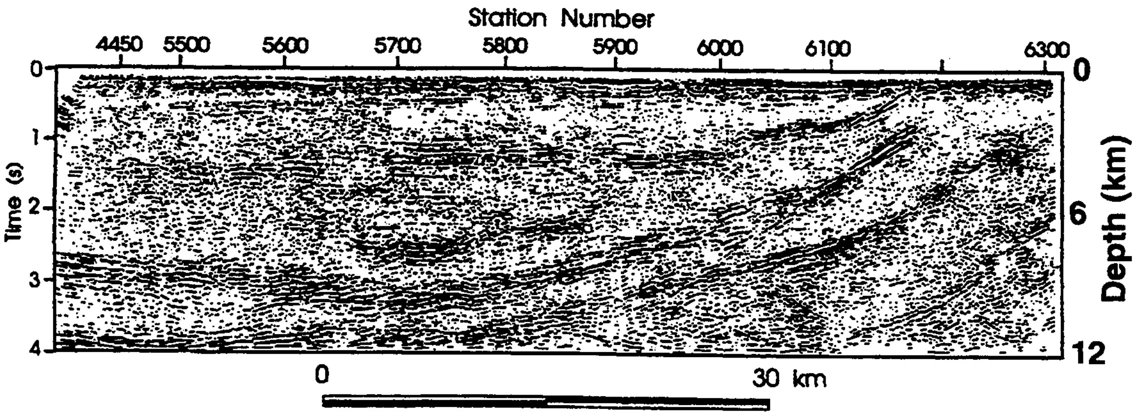


Figure 7-4. Reflection image obtained from reprocessing of the northern part of BABEL Line 1. For location see Figure 7-1. Figure from White (1996).

8 LITHOLOGY AND FRACTURING

8.1 LITHOLOGY

Geological information from the following seven deep borehole locations situated in highly different litho-tectonic environments have been reviewed:

Precambrian Shields;
- The SG-3 Kola borehole
- The Gravberg-1 borehole
- The KLX02 Laxemar borehole
- The SG-8 Krivoy Rog borehole

Variscan orogen;
- The KTB boreholes
- The SG-4 Ural borehole

Alpine mobile belt;
- The Tyrnaus borehole.

Detailed descriptions of the geology in the boreholes are given in Eliasson and Bergström (1996).

Some boreholes were drilled in terrains of large geological complexity, in order to solve geological problems such as ore forming processes (SG-3 and SG-8) and exploration, structure and stratigraphy of volcano-sedimentary sequences, and verification of geophysically predicted crustal structure.

The geoscientific data available from these boreholes emphasise the large structural and lithological heterogeneity both within and between the drill sites. The structural complexity of the continental crust leads to difficulties in predicting the geology in deep boreholes. Major problems are introduced by the presence of large scale orogenic structures such as complex folding, nappes, syn-tectonic thrust faults, and post-orogenic brittle faulting and fracturing.

The Kola, Krivoy Rog, KTB, and Ural boreholes all exemplify the heterogeneity in metamorphosed (i.e. crystalline) and deformed supracrustal rocks. Simple "pancake" models can generally not be used when describing, interpreting, and making extrapolations in volcano-sedimentary formations.

The geological information from the Kola (Figure 8-1) and Krivoy Rog boreholes have demonstrated the unreliability of three-dimensional models of the Proterozoic orogenic belts based on surface geological and geophysical observations (Kazansky, 1992). The predicted and actual geology differ greatly in lithology, tectonic elements and metamorphic grades at great depth. It can be assumed that the composition and structure of the upper continental crust is highly site specific in ancient metamorphic (i.e. pre- and syn-orogenic) Precambrian shield environments.

Geological environments with homogeneous and fairly persistent geology in three dimensions are restricted to large (>1-5 km) intrusive bodies like granitoids. Different types of granitoids are characterised with specific properties, as a result of their tectonic setting and relation to the orogenic development. In particular, post- and anorogenic (i.e., emplaced after the cessation of the latest orogenic event) granitoid plutons and batholiths can be considered to be reasonably predictable regarding three-dimensional shape, composition, and deformation structures.

For example, the Gravberg, Laxemar (Figure 8-2), and Tyrnaus boreholes are all situated in late- to post-orogenic granitic intrusives. Although the penetrated granitic bedrock column exhibits natural magmatic compositional variations, the general predictions regarding the lithology agree fairly well with observations in the boreholes.

Some granite suites, especially the late orogenic types, are commonly related to high heat flow, due to a high content of radioactive elements. All types of granitoids may host mineralisations, such as breccias or disseminations.

On the local scale in some orogenic terrains it can be expected that there is a general increase in metamorphic grade with depth. For example, the Kola borehole displays a distinct increase in metamorphic grade that is compatible with those in comparable strata exposed at the surface (Kremenetsky and Ovchinnikov, 1986). However, the variation of metamorphic grade with depth is highly site specific. The lateral variability in metamorphic grade (as well as the lithology) within the continental crust is evident on most geological maps.

In large fault and shear zones, primary rocks are replaced by broken and crushed (cataclastic) or foliated rocks (mylonites), generally accompanied by different types of alteration and/or metamorphic overprinting. Of special importance are the occurrence of fault breccia and fault gouge. In the cataclastic zones the fine-grained rock powder and, in part, the larger fragments and the wall rock are to some degree commonly affected by low temperature alteration (retrograde dislocation metamorphism). For example, in the Kola borehole, below a depth of 6000 m, ten zones varying between 7 and 74 m in thickness are documented as fault zones with low temperature alteration zones (Glagolev et al., 1987). Low temperature alteration along fault zones are also common in the KTB boreholes (Röhr et al., 1990).

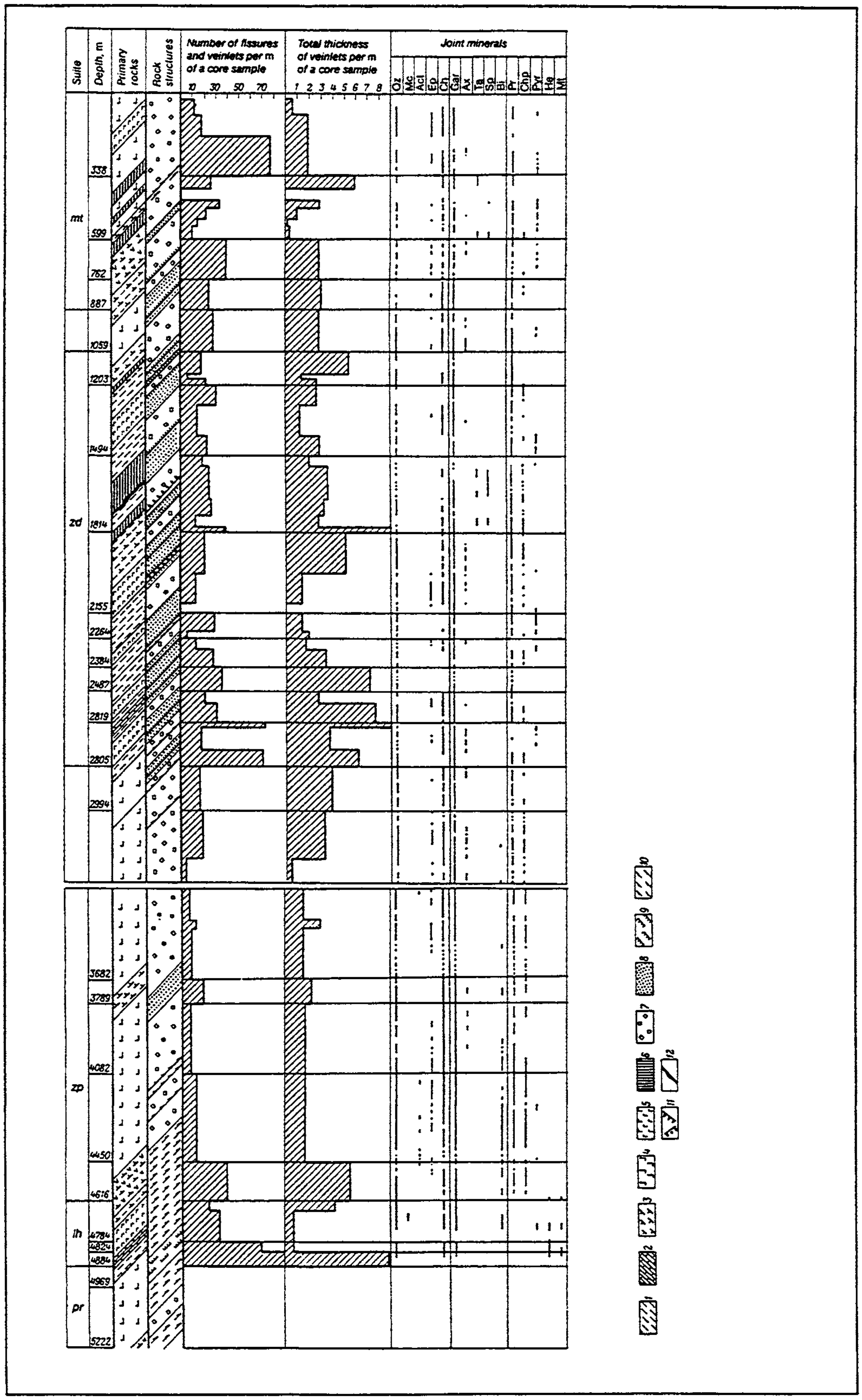


Figure 8-1. Distribution of shear zones, fracture frequency, and mineralised veins in the upper 5 km of the SG-3 borehole (Kazansky et al., 1984). Primary rocks: 1=sandstone; 2=carbonate rocks; 3=basic tuffs; 4=basic lavas; 5=basic intrusive rocks; 6=ultrabasic intrusive rocks; Rock structures: 7=relict massive and globular; 8=relict layered; 9=layered-foliated; 10=crystalline-foliated; 11=cataclastic; 12=ore bodies.

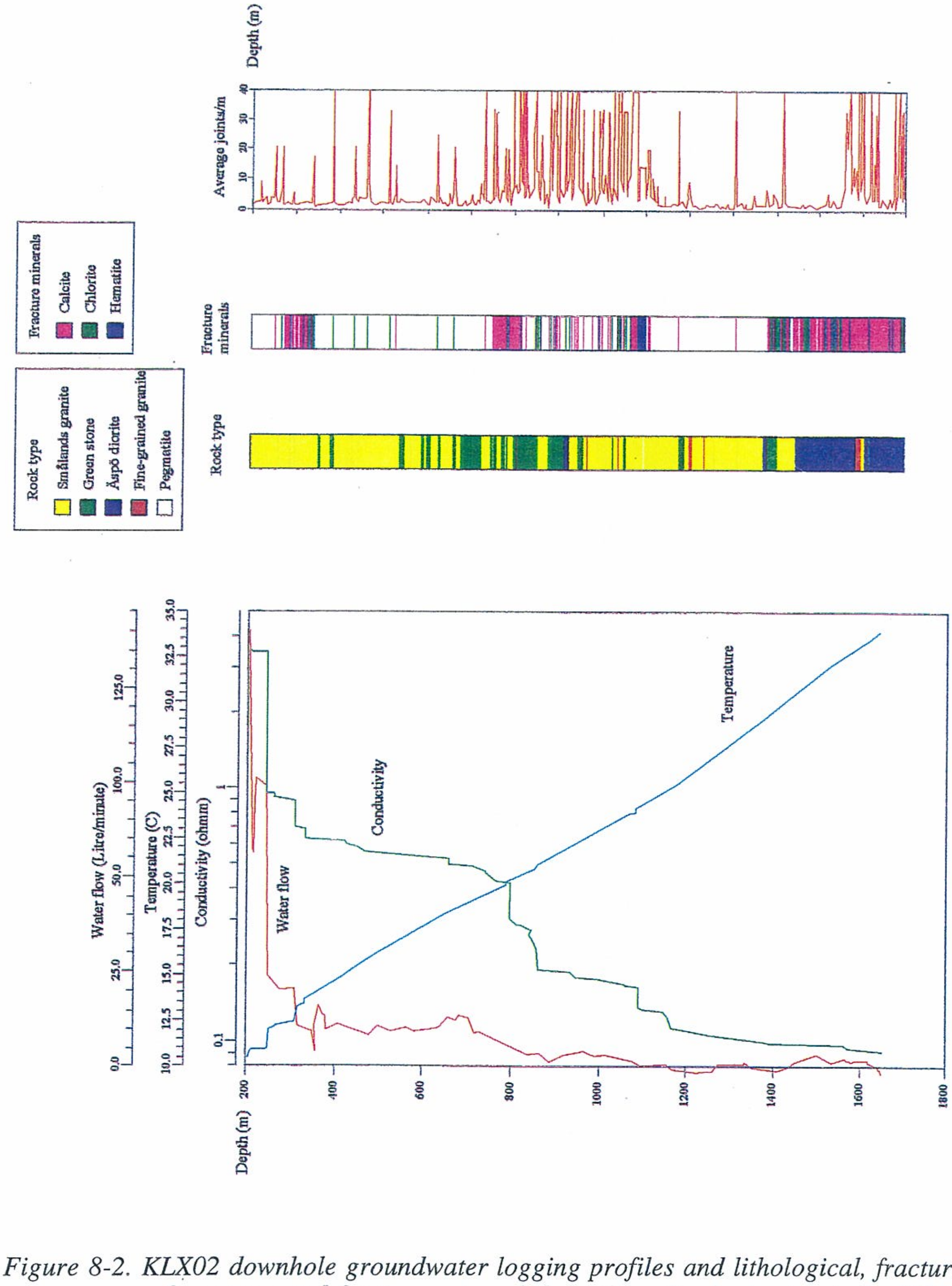


Figure 8-2. KLX02 downhole groundwater logging profiles and lithological, fracture frequency and fracture mineral data (from Laaksoharju et al., 1995). Note the intense fracturing at 700 to 1100 m and below 1560 m.

8.2 FRACTURE MINERALOGY

Natural fractures can be classified into two main categories as regards to their origin (NEDRA, 1992): diagenetic and tectonic fractures. Diagenetic fractures are considered to have developed during, for example, lithification, change of volume, or a metamorphic event. Veins and fracture fillings in such fractures are generally in chemical equilibrium with the surrounding host rock (e.g. quartz and granitic veins in migmatites and gneisses). These fractures are often parallel to the main foliation and associated with a specific stratum of the rock.

Tectonic fractures are related to the post-orogenic development and thereby commonly less site specific. However, of importance are the older pre-existing primary (magmatic or sedimentary) and secondary (folding, foliation, early diagenetic fractures, etc.) structures which partly govern the development of the brittle fracturing. Filling minerals are out of equilibrium with the host rock and not associated with regional metamorphism. This implies that the fractures are often associated with alteration rims along the fracture planes. Kazansky et al. (1984) conclude that fractures and faults with retrograde alteration features are found at depths down to 10-11 km in the Kola borehole.

In the seven locations reviewed the fracture/vein fillings are made up of a great variety of minerals, the most widespread are calcite, chlorite, quartz, and epidote. Subordinately, for example hematite, muscovite/sericite, prehnite, laumontite, adularia, albite/ plagioclase, and sulphides are found. The formation of these assemblages can be constrained by phase petrography to temperatures from about 400°C to as low as 150°C. This implies a formation at temperatures higher than present day conditions in the bedrock and that most of the discontinuities are *reactivated* old structures. Among these assemblages there are some depth related trends in the mineralogical composition, as well as in the composition of the individual minerals of the fracture/vein fillings reflecting higher formation temperatures at greater depths (e.g. Borchardt and Emmermann, 1993). In general, there is a clear dependence of the fracture/vein mineralogy on the lithology of the wall rock.

The composition of recent (formed at present), low-temperature fracture filling minerals in hydraulically open fractures displays a vertical zonality governed by the temperature and the fluid composition. For example the isotopic composition of calcite mirrors the composition of the fluids in the fractures. Furthermore, it can be expected that type and composition of the clay minerals are a function of the depth and, thereby, temperature of formation. Likewise, since the clay minerals are formed largely by chemical degradation/weathering of pre-existing minerals, their composition partly mirrors the wall rock mineralogy.

In the Kola borehole, the number, spatial orientation and mineralogy of fissures depend on wall rock lithology and grade of metamorphism. Quartz (Qz), chlorite (Ch), calcite (Gar) and sulphides (Chp) are found in fractures in all rock types (Figure 8-1). In contrast, serpentinite (Sp) and talc (Ta) are documented only in ultrabasic rocks.

8.3 FRACTURING

8.3.1 Observations from cores and cuttings

The intensity/degree of fracturing in boreholes is commonly presented as fracture frequency, where the number of fractures per a unit length of the borehole is given. As discussed in section 3.3, in order to quantify the virgin conditions at depth in terms of porosity it is important that only natural open fractures are included in the data.

In the KTB and Tyrnaus boreholes there is a significant decrease in fracture frequency with depth, independent of rock type. In contrast, in the Kola borehole, both the frequency and orientation of fractures exhibit a striking correlation with rock composition and degree of metamorphic alteration (see Figure 8-2). An association of increased fracturing to greenstone horizons has also been reported for the KLX02 borehole at Laxemar (Laaksoharju et al., 1995).

Data from the reviewed boreholes do not unambiguously indicate any general correlation between depth and the frequency of fractures (open and healed). Other factors, such as lithology and tectonic situation appear to be more important. However, the methodology used in fracture counting needs to be improved upon, since, in general, no distinction has been made between open and healed fractures.

The macroscale fracture porosity is generally not measured for the core samples due to practical difficulties. Only the porosity of the rock matrix has been measured in the laboratory.

8.3.2 Borehole geophysics

Sonic (velocity) log data from 4 deep boreholes, all in granitic rocks, are presented in Figure 8-3. These are the Gravberg-1 borehole in the Siljan Ring (Juhlin et al., 1991), the RH12 borehole in Cornwall (Parker, 1989), the Böttstein borehole in Switzerland drilled by NAGRA (Holliger, 1996), and the KLX02 borehole at Laxemar (Ekman and Ludvigson, 1998). All four boreholes have been drilled in granitic type rocks from surface to total depth (TD), except for the Böttstein borehole where the upper c. 320 m are sedimentary rocks. Figures 8-4 to 8-6 show the sonic, density and natural gamma logs from the Gravberg-1, Böttstein and KLX02 boreholes. The natural gamma and density logs give an indication of the variation of lithology, although the density is also sensitive to the porosity of the rock.

Extreme lows in the natural gamma log in the Gravberg-1 borehole indicates mafic sills (Figure 8-4). The gamma ray high at 5400 m indicates a felsic quartz monzonite sill. The high at 3200 m to 3300 m indicates a quartz rich zone where drilling was extermely slow. Other minor highs are zones with increased Th and U content indicating possible zones of increased fluid circultation in the past. Aside from these variations, the log indicates that there are two primary lithologies present, a more felsic granite above 1000 m and a more mafic one below 1200 m. Several studies (Juhlin, 1990; Moos and Zoback, 1983) have shown that low sonic velocities in crystalline rock correspond to fracture zones. The upper 1200 m of the Gravberg-1 borehole has been documented to be more fractured than the rocks below (Juhlin, 1990). It could be argued that the upper

1200 m in the Gravberg-1 borehole is more fractured due to the rock being more quartz rich and, therefore, more brittle. However, a similar pattern is observed in the Stenberg-1 borehole about 10 km to the south where the rock is more fractured down to about 1300 m (Figure 8-7) in a more mafic granitic environment (Papasikas and Juhlin, 1997).

The Böttstein borehole shows a relatively homogeneous granite, from a compositional point of view, in the crystalline portion of the borehole (Figure 8-5). The same is true for the granite in the RH12 borehole (Parker, 1989). In contrast, the KLX02 borehole shows significant variation in the lithology with one rock type having a density of about 2.7 g/cc and the other a density of about 2.9 g/cc. Regardless of rock type, all four boreholes show a similar pattern, the upper 1000-1200 m of rock shows considerably more variation in sonic velocity than the rock below. This variation manifests itself in that low velocity zones are more common above this depth and the velocity within these zones is generally lower than in the deeper ones.

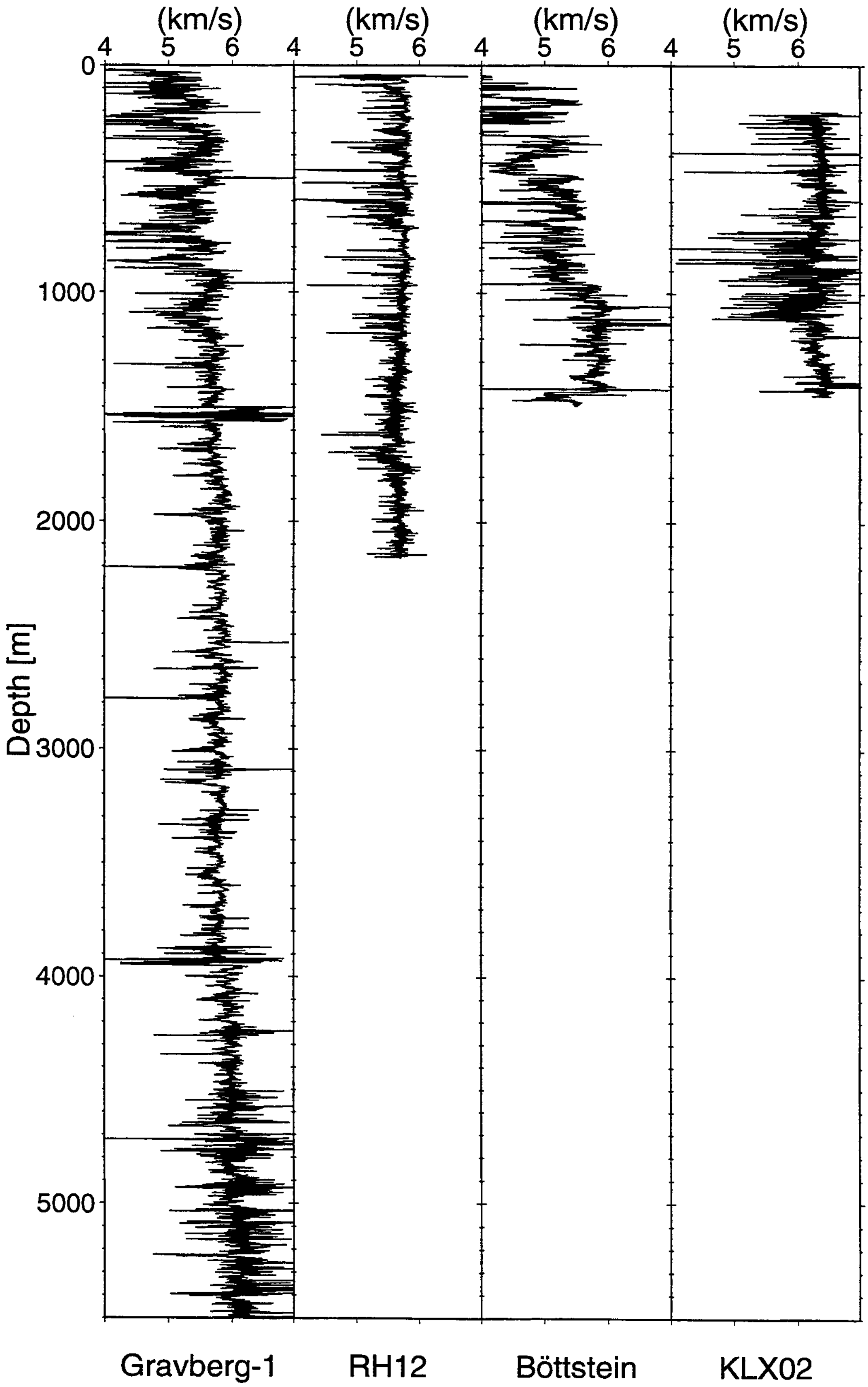


Figure 8-3. Velocities from sonic logs in four deep boreholes in granitic rock. The data are raw except for editing of obvious cycle skips on the Gravberg-1 and RH12 sonic logs.

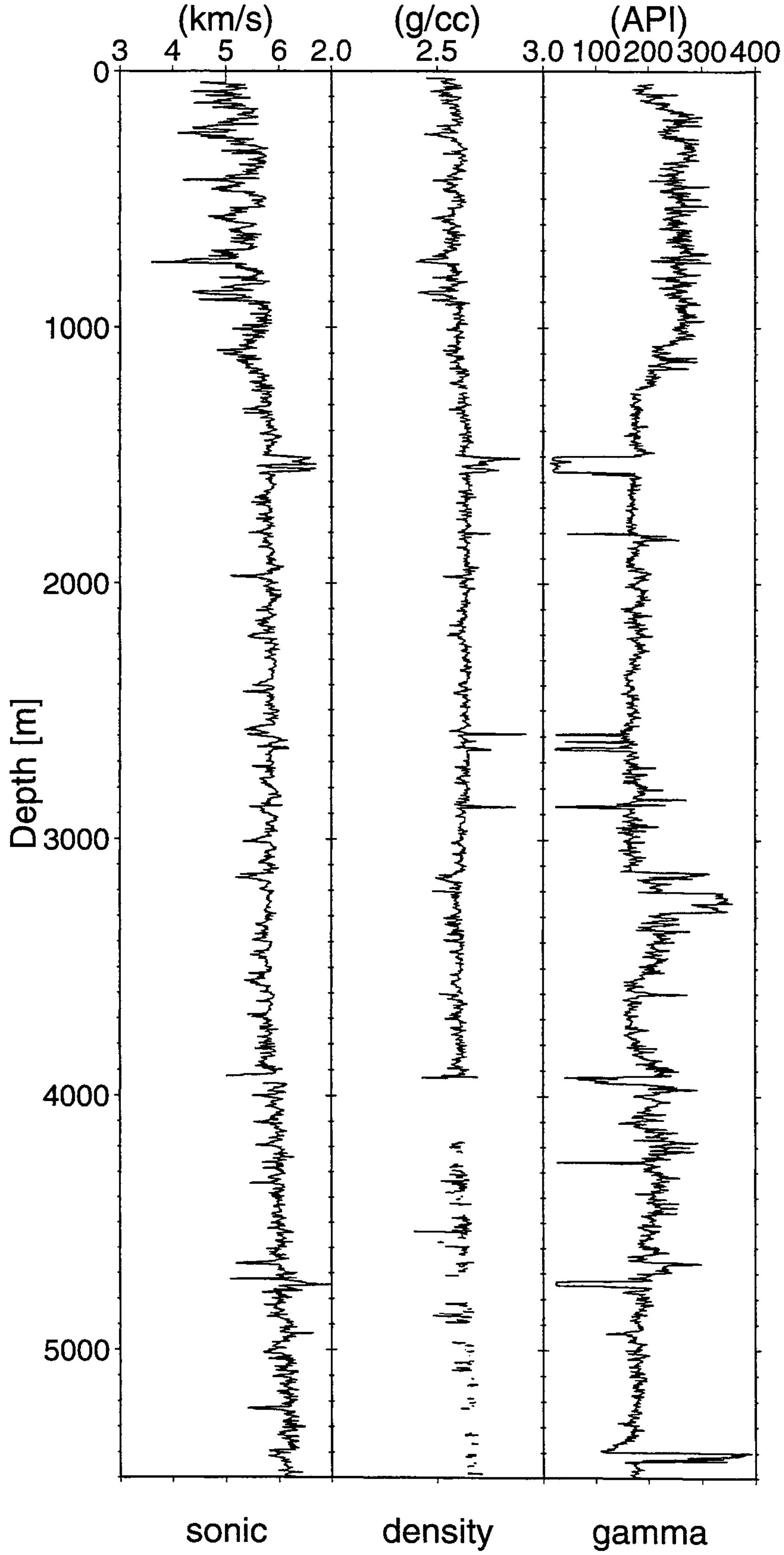


Figure 8-4. Velocity, density and natural gamma logs from the Gravberg-1 borehole. The data have been corrected for geometric effects and smoothed over 1.5 m intervals.

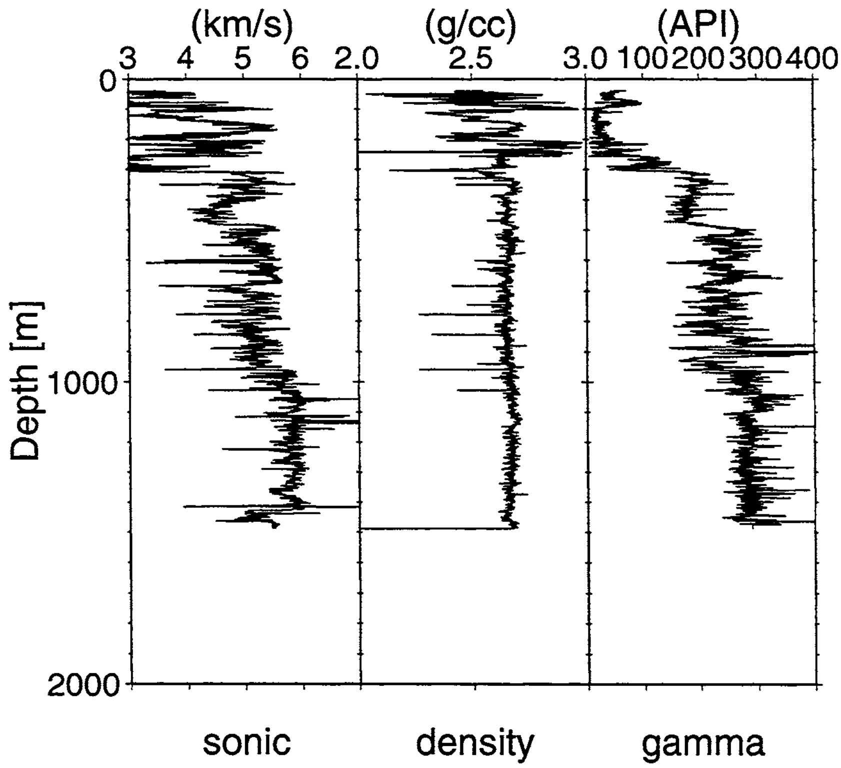


Figure 8-5. Velocity, density and natural gamma logs from the Böttstein borehole. The data are raw and no editing or geometric corrections have been applied.

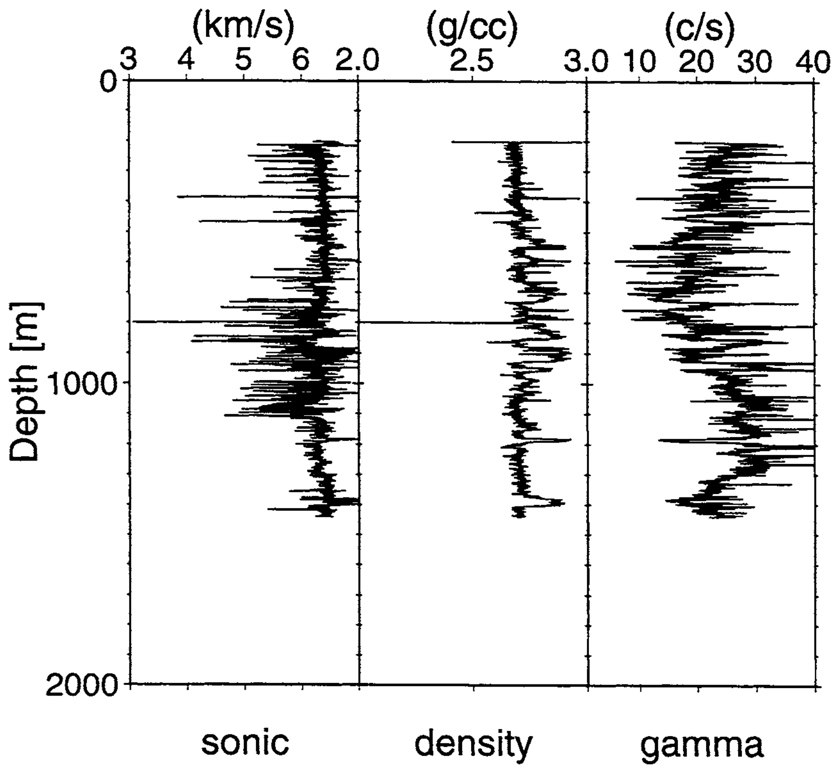


Figure 8-6. Velocity, density and natural gamma logs from the KLX02 borehole. The data are raw and no editing or geometric corrections have been applied.

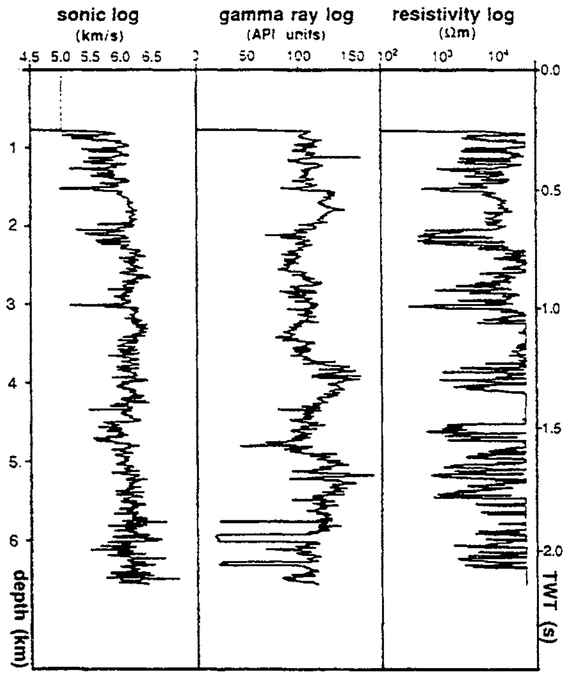
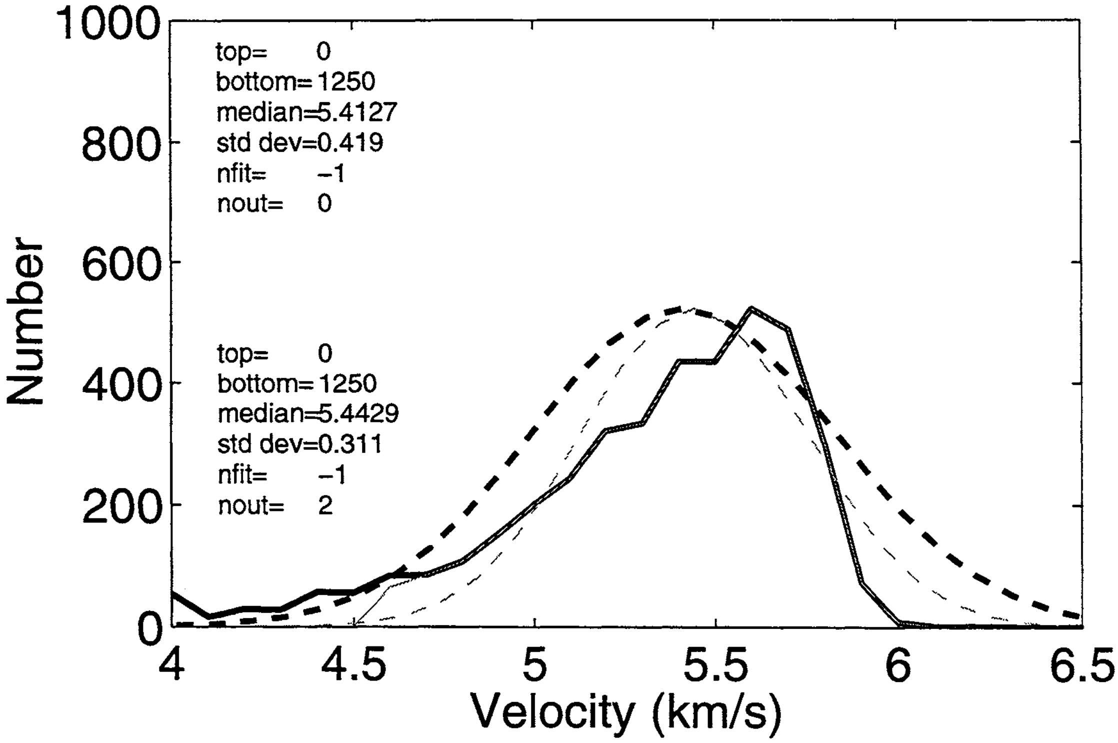


Figure 8-7. Geophysical logs from the Stenberg-1 borehole (from Papasikas and Juhlin, 1997).

A more quantitative analysis of the sonic log from the Gravberg-1 borehole is shown in Figure 8-8 where the velocity distribution in the upper part and lower part of the borehole has been plotted. The actual distributions tend to be Gaussian, but are skewed to the low velocity side. If it is assumed that intact granite has a velocity distribution which is Gaussian due to compositional variations then the skew to the low velocity side can be explained by fracturing since the presence of fractures will only decrease the velocity and never increase it. The greater the skew, the greater the amount of fracturing in the interval being analysed. Similar patterns are observed in the other three boreholes with the upper c. 1000 m having considerably more skew towards low velocities than the rock below. However, the differences between the upper part and lower part are not as dramatic as for the Gravberg-1 borehole. A qualitative rating of the amount of fracturing based on the skewness as shown in Figure 8-8 would give the Gravberg-1 borehole as being the most fractured in the upper part, then the Böttstein borehole, followed by KLX02, and the RH12 as the least fractured in the upper part.



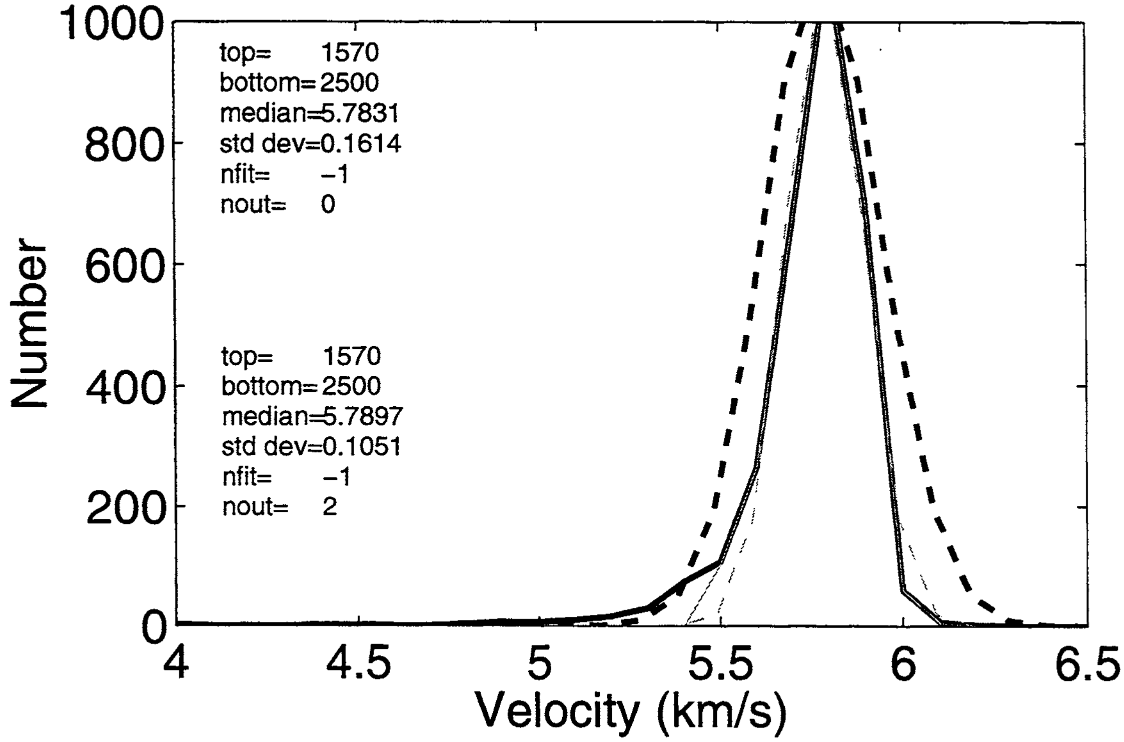


Figure 8-8. Velocity distribution for the upper part (upper plot) and the lower part (lower part) of the Gravberg-1 borehole. Intervals analysed are shown on the plots. Shown are actual distribution (heavy solid line), modified distribution when samples outside of 2 standard deviations are omitted (thin solid line), Gaussian fit to actual distribution (heavy dashed line) and Gaussian fit to the modified distribution (thin dashed line).

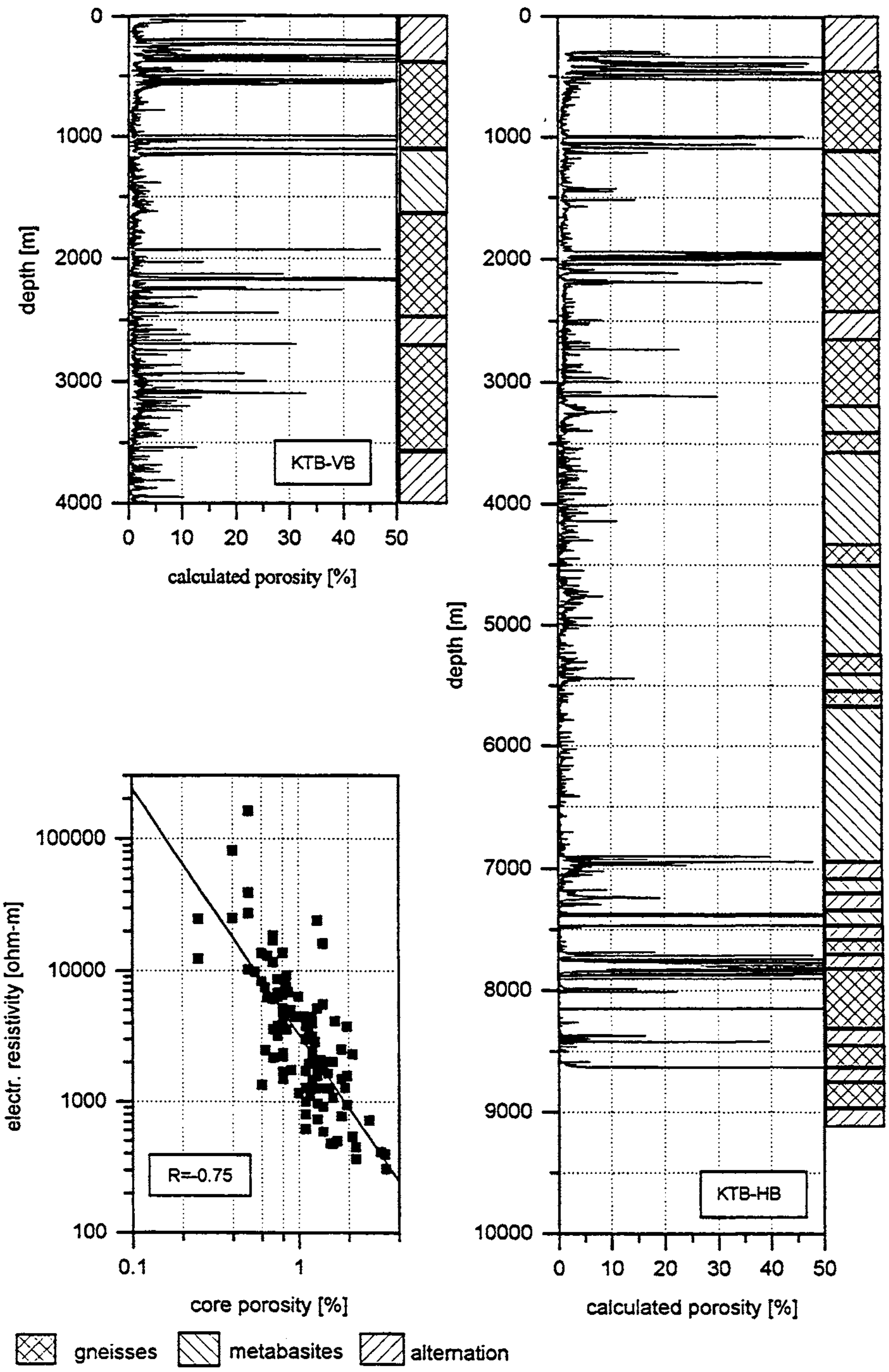


Figure 8-9. Porosity logs from the KTB pilot and main hole calculated from the resistivity log based on calibration with core data. From Pechnig et al. (1997).

The KTB pilot hole and main hole in Germany have been drilled to 4001 m and 9101 m, respectively. Extensive analyses of the geophysical logging data have been carried out including the calibration of log porosity with core porosity (Pechnig et al., 1997). Porosity profiles for the two holes are shown in Figure 8-9 where the porosity has been calculated from the resistivity log using Archie's law. The logs indicate the upper 500 to 600 m to be more fractured than below. However, fracture zones are present down to 9 km with significant fracture zones below 7 km. The logs were calibrated on core samples containing up to 4% porosity. Therefore, porosity values above about 5% should only be considered as apparent porosity. The extreme values (>10%) are influenced by the presence of graphite and ore minerals in the fracture zones.

8.3.3 Surface geophysics

There has been recent interest in analysing surface waves from refraction experiments to estimate the S-wave velocity structure and attenuation in the upper few km of crystalline crust in the Baltic Shield. Areas studied are southern Sweden (Åström and Lund, 1994), central Finland (Grad and Luosto, 1994) and eastern Finland (Pedersen and Campillo, 1991). Results from these studies show the S-wave velocity increasing rapidly in the upper 1 km of crust and then increasing more slowly (when there is enough resolution in the data). Typical S-wave and P-wave velocity functions are shown in Figure 8-10. The S-wave velocity model presented in the figure is not limited to the Baltic Shield. Similar observations have been made on the Arabian Shield (Mokhtar et al., 1988). Analyses of Rayleigh (Rg) waves from earthquakes on stationary seismic arrays indicate a similar S-wave velocity structure in the upper crystalline crust (Ruud et al., 1993).

The behavior for Q, which is inversely proportional to the amount of attenuation of seismic waves, is similar in central Finland with low Q (high attenuation) in the upper 1000 m and then increasing to higher values (lower attenuation). A similar Q structure for P-waves was reported in the Grängesberg area in Sweden (Båth, 1985) and in the Gravberg-1 borehole (Juhlin, 1990). Analysis of the P-wave velocity structure in the uppermost crust of Sweden also indicates that the velocity increases rapidly in the upper km of crust, and then increases more gradually (Båth, 1985; Hossain, 1989). Furthermore, analysis of the ratio of P-wave velocity to S-wave velocity in Sweden (Hossain, 1989) and Finland (Grad and Luosto, 1994) shows that it is relatively high close to the surface and then decreases rapidly down to 1-2 km, and then stays nearly constant. This decrease is consistent with the amount of fluid filled cracks becoming significantly less below 1-2 km.

Velocity data have not been compiled from areas consisting of younger crystalline rocks at this time, but in the Palaeozoic Urals a strong velocity gradient in the upper few km is not observed (M. Bliznetsov, personal communication, 1992).

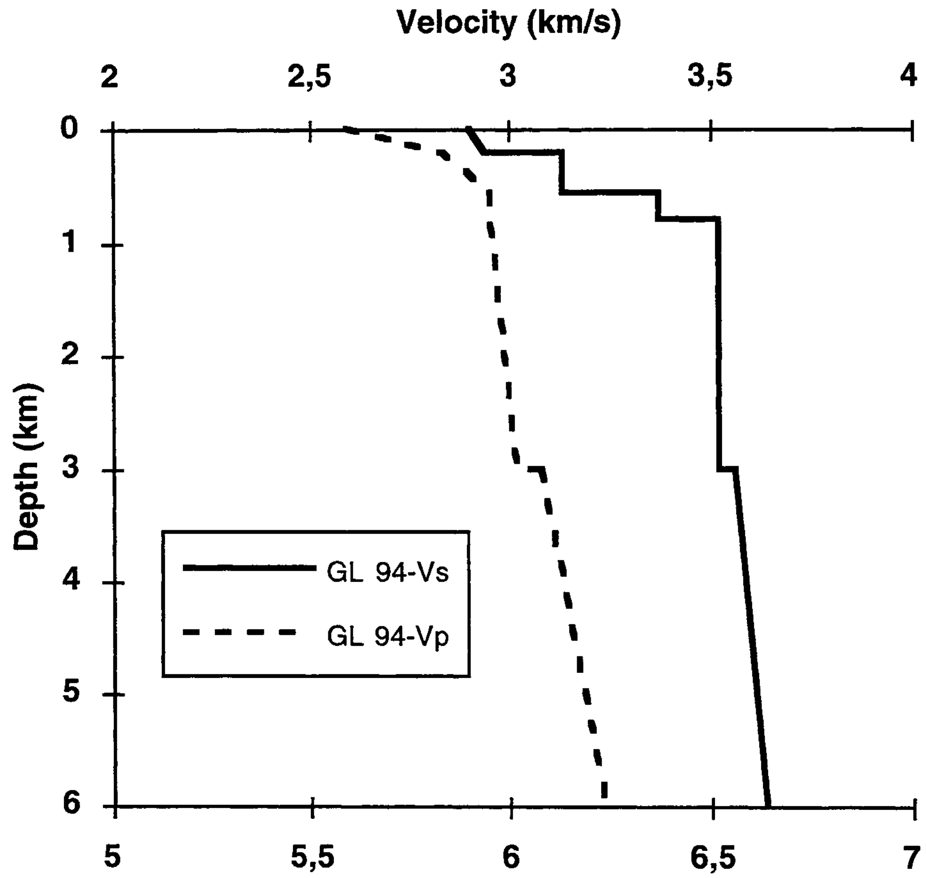


Figure 8-10. P-wave and S-wave structure from central Finland (Grad and Luosto, 1994).

9 TEMPERATURE

An inventory of heat flow in the Baltic Shield was carried out in 1992 during the European Geotraverse (EGT) project (Blundell et al., 1992). The estimate of surface heat flow is based upon measurements in shallow boreholes. Figure 9-1 shows the distribution of the measurements in Sweden and Figure 9-2 shows the heat flow along a N-S profile. In general in the Baltic Shield, the apparent heat flow calculated from boreholes penetrating a few hundred metres into the bedrock will be 5-15 mW/m^2 lower than the true heat flow due to climatic changes with the smaller correction being suitable for the north and the larger correction for the south.

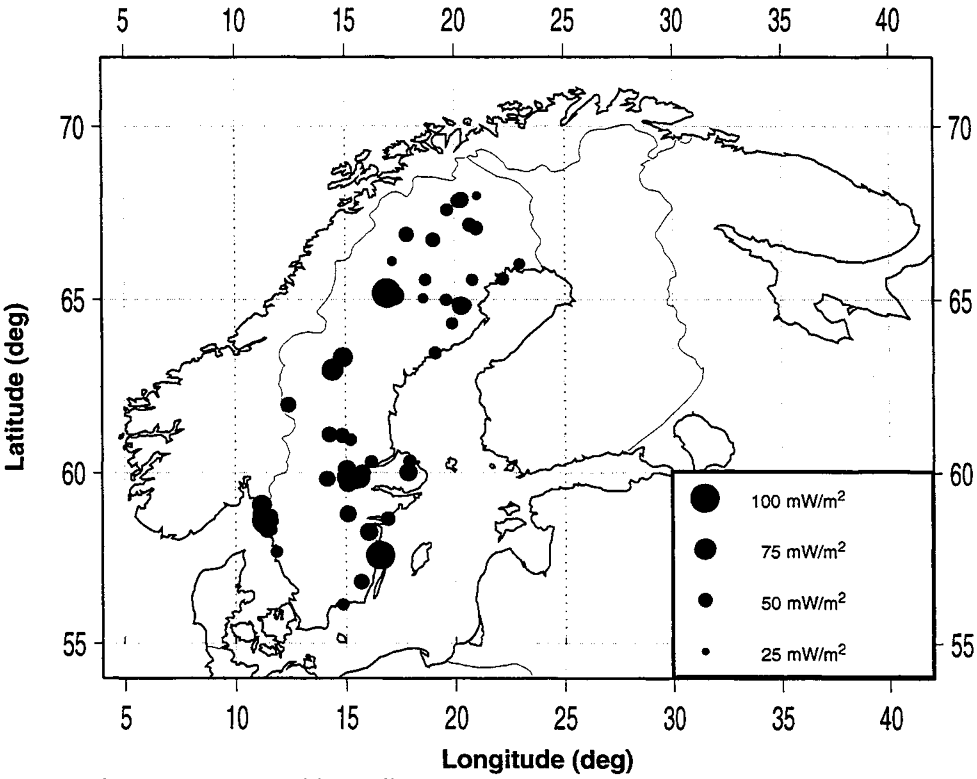


Figure 9-1. Location of heat flow measurements in Sweden.

A number of studies have been carried out to predict the temperature at 500 m depth in Sweden based on heat flow observations and assumptions of the thermal conductivity and heat production at depth (Ahlbom et al., 1995; Eliasson and Lundqvist, 1994; Sundberg, 1995). The thermal conductivity and heat production estimates are based on measurements of rock samples which are often relevant for the areas under study. These studies predict temperatures of about 7.5° C in northern Sweden and about 15° C in southern Sweden at 500 m depth. Similar methods may be used to extrapolate the temperature to the depth interval 1 km to 5 km. These give a maximum temperature of about 80-105° C at 5 km if the temperature gradient is 15-20°/km. These temperature gradients are also predicted in the uppermost crust from lithospheric modelling of heat flow in the Baltic Shield (Balling, 1995). However, in the study by Ahlbom et al.

(1995) the observed gradients in 11 selected areas in Sweden are generally less than 15°/km implying that the temperature at 5 km may on average be somewhat less than 80° C and possibly as low as 60° C in some areas. The sites studied in Ahlbom et al. (1995) are believed to be representative for Sweden and the temperature gradients were calculated in boreholes which extended, generally, to at least a depth of 500 m.

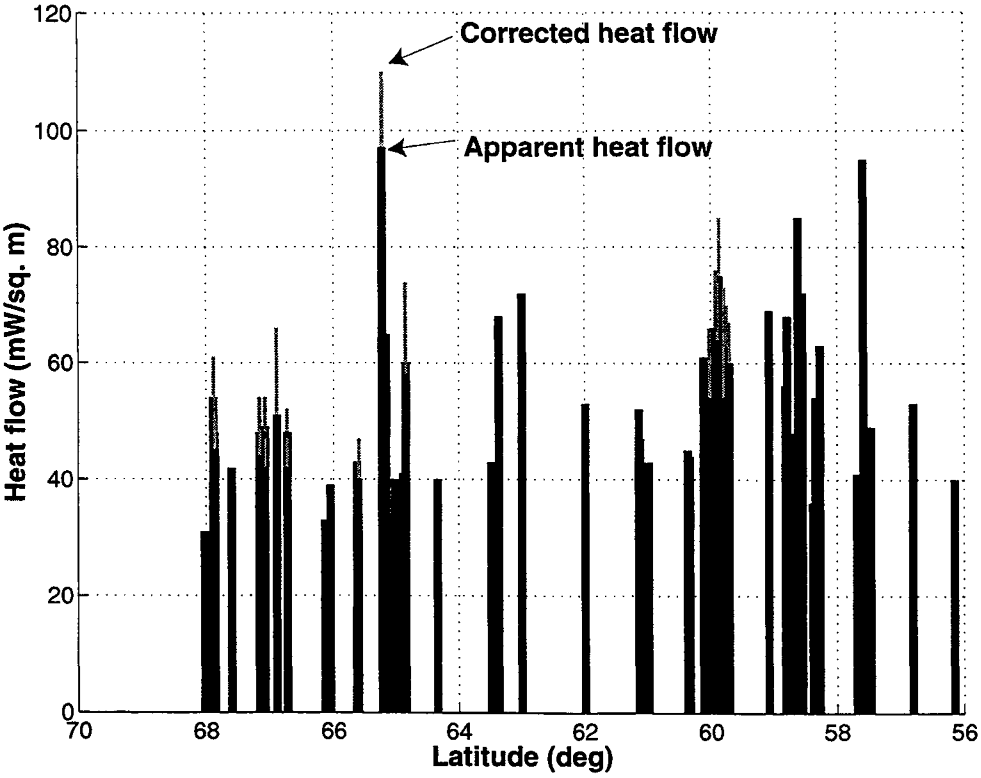


Figure 9-2. A N-S profile in Sweden of observed heat flow and corrected heat flow. Note, not all observations have had corrections applied. Data from Blundell et al. (1992).

The temperature gradient in the Gravberg-1 borehole is nearly constant at about 16°/km, this is similar to that observed at Laxemar. Variations in the temperature gradient in the Gravberg-1 borehole are probably due to groundwater entering the borehole at the time of logging. The temperature gradient in the SG-3 borehole on the Kola peninsula in Russia changes abruptly at 2800 m depth from about 13°/km to about 17°/km (NEDRA, 1992). The reason for this increase in temperature gradient is not clear from the literature. Although some details of the temperature variation with depth are not clear, the observed temperatures in the deep boreholes in the Baltic Shield agree well with those predicted from heat flow observations.

10 HYDROGEOLOGY

Within the Baltic Shield, in-situ permeability measurements from depths greater than 1000 m have been reported from three sites, Gravberg (Gustafson and Rhén, 1990), Kola (NEDRA, 1992), and Laxemar (Follin, 1993). The data from these sites have been compiled in Figure 10-1.

Since these data provide too small of a database to allow any major conclusions, additional data from measurements in crystalline bedrock in other parts of the world have been supplemented in Figure 10-2. These data have been divided into two groups, *Other shield areas and stable platforms* and *Other crystalline bedrock*. The criterion used to select the data used was that the measurements must represent natural, undisturbed conditions (Wallroth, 1996). Additional data for representative bedrock exist in the reports and papers from the hot dry rock (HDR) geothermal energy research sites. However, these data have not been included since they reflect either hydraulic conditions after major hydraulic fracturing and fluid injections, or tests carried out at pressures high enough to induce significant fracture dilation and temporarily enhanced permeabilities.

We can see in Figure 10-2 that even after introduction of these data, the information from large depths is very limited. For comparison, the approximate range of permeabilities measured at SKB's study areas are also shown. The overall range of in-situ permeability values (10^{-19}- 10^{-13} m^2) from large depths agrees well with other compilations for crystalline rocks, e.g. Brace (1984), who reported the range 10^{-18} -10^{-13} m^2 for depths down to 3 km. Clauser, (1992) compiled data from different types of experiments and studies in crystalline rock in an attempt to relate the data to scale effects. Clauser's data for borehole investigations fall generally within the range 10^{-20} -10^{-12} m^2.

The data compiled in Figures 10-1 and 10-2 represent in most cases transmissivity values divided by the length of the test section, which varies between one metre and about four kilometres. This implies that the effect of a highly permeable zone within a long, more or less impermeable borehole section is smoothed out. Higher permeabilities than those indicated in these figures can therefore be expected locally, especially within the long borehole sections.

Published analyses of depth trends in permeability down to 300-900 m in crystalline bedrock often show a zone of higher permeability in the upper 100-300 m. Below this zone the permeability appears to be roughly constant or decreases very slowly.

According to Figure 10-2, there appears to be a clear decrease in bulk permeability with depth. An interesting observation is the apparent log-linear decrease for the largest permeability values. The highest values observed seem to be about three orders of magnitude lower at 5000 m than at 1000 m. The number of measurements at depths greater than 2000 m are, however, rather few, and the data base is not considered sufficient to allow far-reaching conclusions to be drawn. A reservation should also be made with respect to the variations in section length described above.

There are two aspects of extrapolation that can be distinguished. One deals with the use of surface data as a means of making general predictions at great depths. Regression lines fitted to data from the upper 500-900 m at some of SKB's study areas produce extremely varying permeability estimates at depth (Wallroth, 1996). However, the compilation shown in Figure 10-2 indicates a vague possibility to estimate the highest permeability that can be expected at various depths to an order of magnitude.

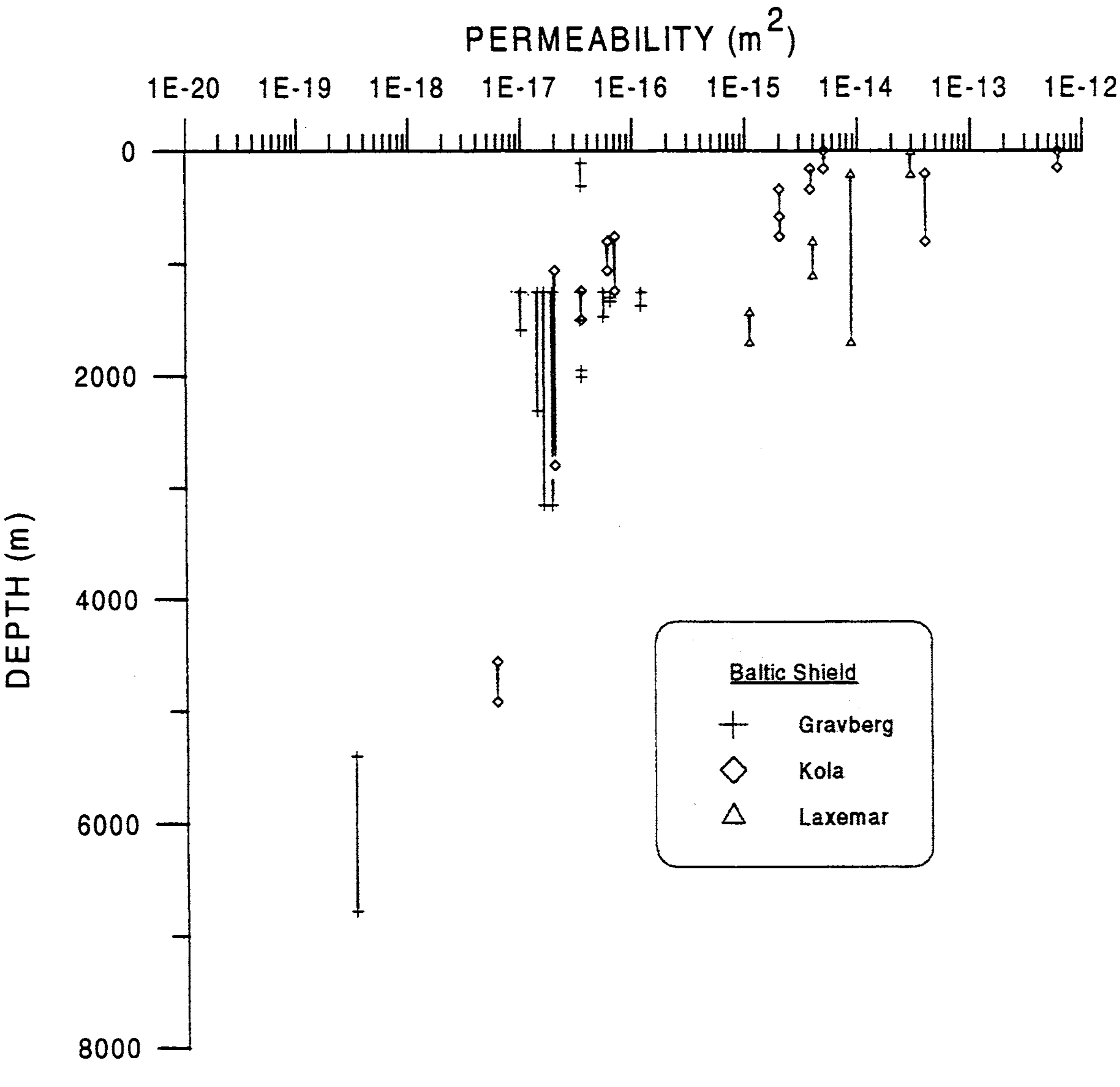


Figure 10-1. Compilation of permeability measurements in boreholes in the Baltic Shield.

The other aspect of extrapolation means a site-specific prediction, where shallow in-situ data are used to estimate the local hydraulic conditions at depth. However, none of the sites reviewed in this report have offered a large enough quantity of data over a large enough depth interval to enable such a trend analysis. This type of study would also require a combined use of detailed geological and hydraulic data.

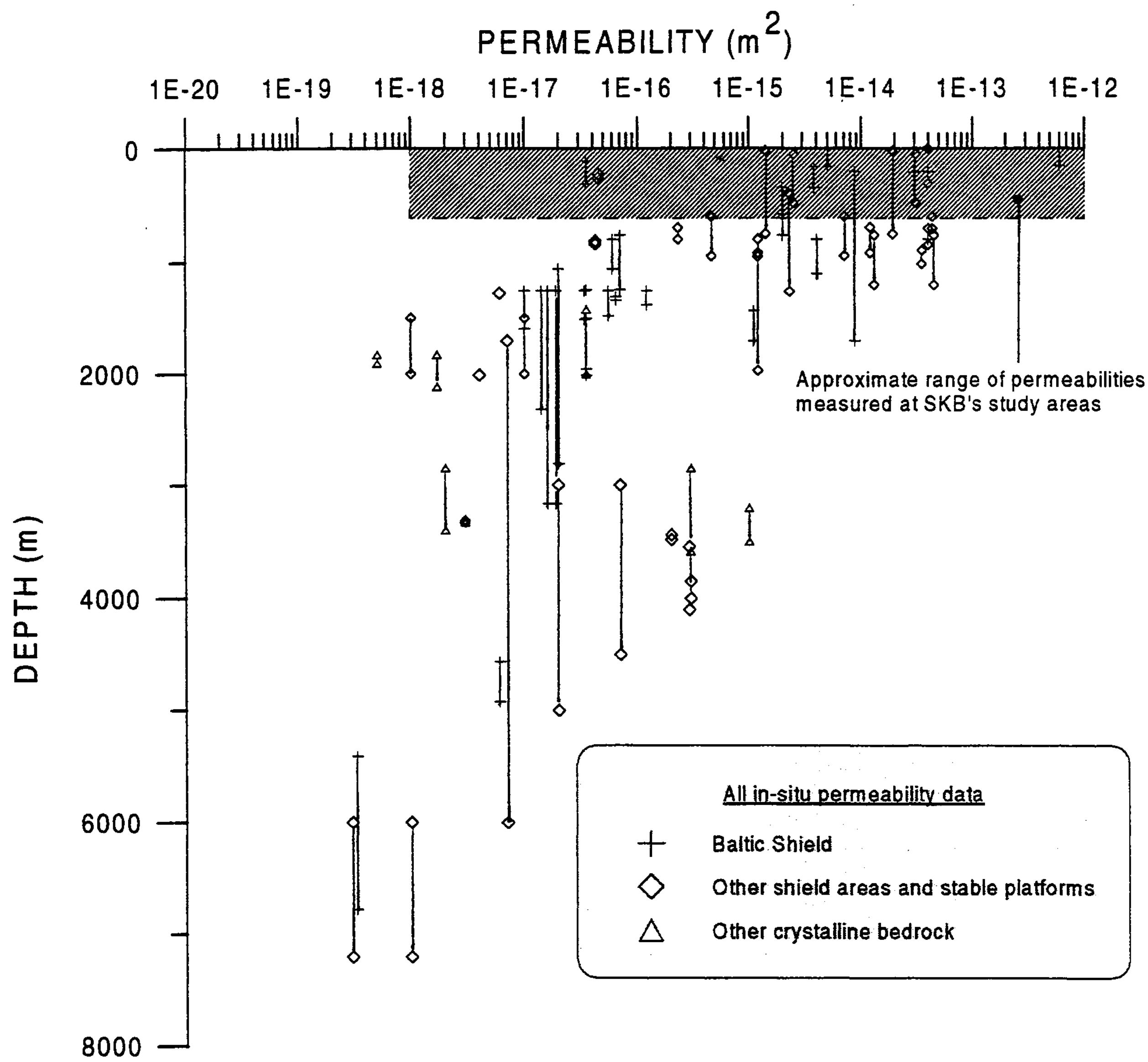


Figure 10-2. Compilation of permeability measurements in boreholes in the Baltic Shield and other areas. References can be found in Wallroth (1996).

+ - Gravberg, Kola, Laxemar

♦ - KTB, Germany; Krivoy Rog, Ukraine; Rosemanowes, England; Siblingen, Switzerland

- Soultz, France; Cajon Pass, USA; Fenton Hill, USA, Urach, Germany; Sancerre-Couy, France)

Only occasional information on pore pressure at depth in representative geological environments has been presented in the literature. Gustafson and Rhén (1990) reported indications of pore fluid pressures slightly below hydrostatic from the deeper part of the Gravberg-1 borehole. From most of the other deep drillings reviewed, pressures 2-5% higher than hydrostatic have been reported. However, for the depth range 1000-2800 m in the Kola borehole NEDRA (1992) described some fault zones where the hydrostatic pressure was exceeded by 40-50%. Observations in deep mines in the Canadian Shield (see section 13.3) have also revealed fractures with pressures significantly above the hydrostatic pressure.

11 MECHANICAL PROPERTIES AND STATE OF STRESS

11.1 MECHANICAL PROPERTIES

As discussed earlier in this report, strength and deformability of rock masses depend on:

- The rock material as such.
- Geometrical parameters such as volume and shape of the rock volume of concern.
- Boundary conditions, in particular confinement and temperature.

Since confinement (ambient stress) and temperature both increase with depth, rock mass mechanical characteristics will indirectly be depth-dependent. There are two principally different methods available to determine this depth-dependency for the parameters of concern. One is to conduct laboratory tests where appropriate confinement and/or temperature is simulated. There is a wealth of data available from such testing, on rocks from the Baltic Shield as well as from other parts of the world. Especially the effect of confining stress has been extensively studied because of the major implications this effect has in rock engineering applications. The obvious drawback with laboratory testing is the limitations in test volume. Important scale effects are difficult to assess.

The other approach is actual observation of natural or induced mechanical phenomena, from which parameters can be back-calculated. Thus, seismic (and other) information from natural or induced fault shear movements can provide data on e.g. frictional characteristics of large-scale discontinuities such as faults. A fundamental problem with the observational approach is that information on parameters like boundary conditions, the geometry involved, etc. is usually insufficient.

To estimate the mechanical properties within the depth range 1000 m - 5000 m we first consider data on compressive strength and Young's modulus, obtained from laboratory testing. Typical compressive strength values for granitic rocks in Sweden tested under unconfined conditions vary between 140 - 220 MPa. Typical values on the Young's modulus are between 45 - 80 GPa, and between 0.15 - 0.25 for the Poisson's ratio.

Compressive strength and Young's modulus tests on Stripa Granite (Swan, 1978) indicate a strength increase on the order of 250%, and a Young's modulus increase on the order of 15%, as the confinement was increased from 0 to 30 MPa (0 to c. 1 km).

If the confinement at 5 km depth is equal to the minimum stress, then the strength of intact rock should increase from some 200 MPa at shallow depth up to at least 600 MPa at 5 km depth. The Young's modulus (intact rock) would increase from some 60 GPa up to approximately 80-85 GPa.

The discussion above only applies for intact rock, where no weak features intersect the samples. If zones of weakness are present, irrespective of scale, this will affect both strength and deformability. Hence, when discussing stability on a larger scale, including fractures and fracture zones, it has to be assumed that stability will be controlled by other factors than those investigated by intact rock testing.

The investigation programme for the KTB pilot borehole included laboratory determination of strength and deformability on specimens between depths of 189 m and 3559 m. Testing was conducted on metabasites and biotitic gneisses. For all parameters determined (uniaxial compressive strength, modulus of elasticity and tensile strength), and for each rock type penetrated by the borehole, there are indications of increasing values with depth (Röckel and Natau, 1990). Not surprisingly, large variations occur between the different rock types.

Similar testing was undertaken in the superdeep Kola borehole, the Krivoy Rog superdeep borehole and the Tyrnaus deep borehole (NEDRA, 1992). Due to the local variations in lithology, however, it is difficult to draw any conclusions from the tests conducted on specimens from the Kola and Krivoy Rog boreholes. In the Tyrnaus borehole, testing of the uniaxial compressive strength and the tensile strength was conducted on grey granite samples taken from 715 m depth down to 3835 m. The uniaxial compressive strength decreases with approximately 28% from the uppermost tests to the deepest, and the tensile strength decreases with 30-35%. Any explanations for the decrease in strength characteristics with depth are not found in the NEDRA report.

The shear deformational behaviour of rock fractures is complex and depends on the frictional and topographic characteristics (extent and geometry of asperities) of the joint surfaces, the strength of the rock material forming the surface asperities, and on the effective normal stress acting across the joint plane.

The shear strength of joints can be described with a Coulomb type relationship:

$$\tau_s = c + \sigma_n \tan \phi \qquad (11\text{–}1)$$

where τ_s is shear strength, c is cohesion or "inherent strength" of the joint, σ_n is effective normal stress, and ϕ is apparent friction angle.

The cohesive component is zero for open fractures. The apparent friction angle describes the total, stress dependent shear resistance and may, thus, involve contributions from both "true" surface friction and effects related to surface roughness. A peak shear strength envelope typically shows a curved relationship whereas the residual strength usually is a near-linear function of the normal stress. The curvature in the peak shear strength envelope reflects stress dependency in which surface roughness influences the shearing process. At low normal stresses, asperities tend to override each other, causing separation (dilation) of the joint surfaces. Higher normal stress increases asperity damage, whereas very high normal stress precludes dilation and the asperities are completely sheared off.

As for other rock parameters there also exists a scale dependency for the shear strength. The most widely adopted procedure to determine joint shear behaviour is the set of relationships developed by Barton and co-workers (Barton and Bandis, 1982; Barton and Choubey, 1977). One of several observations from Barton´s work is that the shear displacement required to mobilise peak shear strength increases with increasing block size.

Normal deformation of rock joints generally contributed to a major part of the bulk deformability of jointed rock masses. Joint deformation is also responsible for most of the stress dependency in rock mass deformability that is often observed. The influence of the joints decreases with increasing stress, and at high confinement the rock mass deformability approaches that of the intact rock.

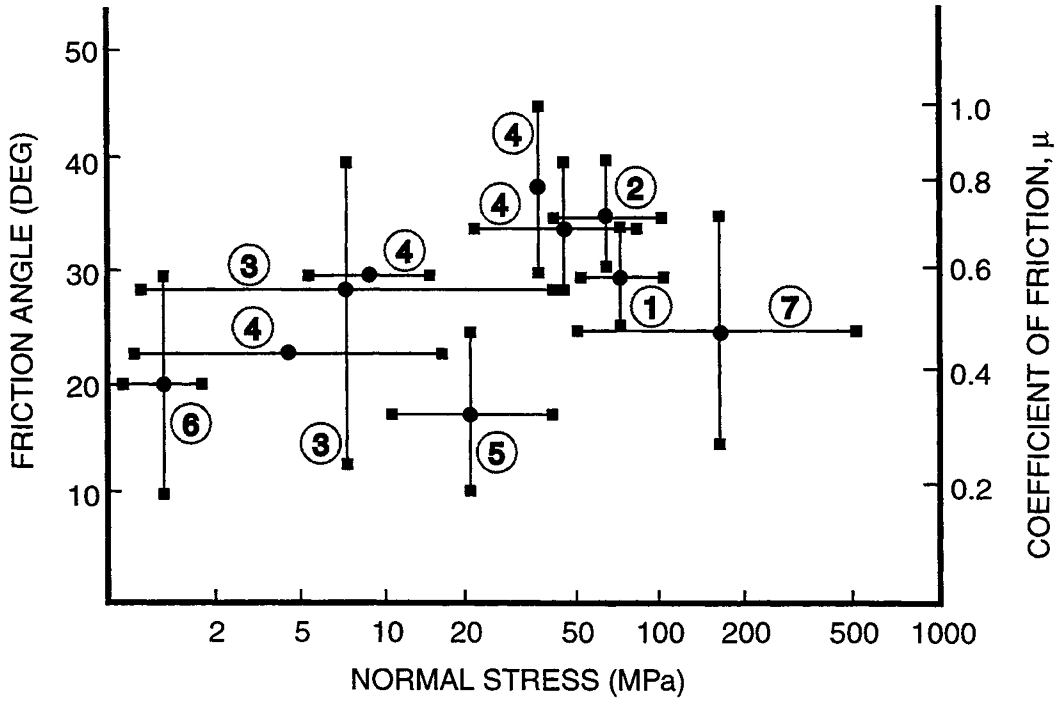


Figure 11-1. Friction angle and coefficient of friction as function of normal stress. Horizontal and vertical bars indicate approximate ranges for normal stress and friction respectively (after Leijon, 1993).

1) Faults in South African gold mines, modelling and field observation.

2) Strathcona mine, modelling and field observation.

3) Back-calculation from stress measurements - general data (Jamison and Cook, 1978).

4) Back-calculation from stress measurements in areas of active faulting (Zoback and Healy, 1984).

5) Weak contact zones in Swedish mines, modelling and field observation.

6) Common discontinuity filling materials, laboratory and field testing.

7) Fault gouge material, laboratory testing.

Scholz (1990) and Leijon (1993) discussed the concept of frictional balance where the rock mass is in an unstable state of equilibrium and the state of stress balances the frictional strength. It follows that application of additional deviatoric load will disturb the equilibrium and cause deformation by shear failure resulting in stress redistribution such that equilibrium is re-established. Since large discontinuities constitute the weak links in the bedrock along which adjustments would reasonably occur, the theory offers opportunities to infer strength properties of such structures. The validity of the concept on different scales, for different stress regimes, at different depths and in different parts of the world, has been subject to considerable discussion.

Jamison and Cook (1978) applied the concept of frictional balance to infer frictional strength from stress measurements. Stress data were obtained from measurements reported from some 50 locations scattered around the world. The data set represented depths down to 2000 m and stress levels up to some 50 MPa, although the majority of the data came from depths less than 400 m. The analyses were restricted to cases where one of the principal stresses were found to be vertical and approximately equal to the lithostatic stress. This was partly done in order to allow the data to be grouped into three subsets of faulting regimes; normal faulting (maximum stress vertical), thrust faulting (minimum stress vertical) and strike slip faulting (intermediate vertical stress). From Jamison and Cook's (1978) work, friction angles ranging from 32° (thrust faulting) to 12° (strike-slip faulting) were back-calculated. A summary of their results and others are found in Figure 11-1. There is an apparent increase of friction angle with normal stress, but the data are to scattered to draw any far-reaching conclusions.

11.2 STATE OF STRESS

11.2.1 Shallow data

A description of the most common stress indicators and a compilation of deep stress measurements in crystalline rock world-wide is presented in Ljunggren and Leijon (1996). With very few exceptions, data from stress measurements in Sweden and within the Baltic Shield have been obtained from depths less than 1000 m.

Most published results from in-situ stress measurements in Sweden have been compiled in a stress data base (Ljunggren and Persson, 1995). Assuming a linear relationship between stress magnitude and depth, regression analyses of data stored in this data base gives the following expressions for the maximum (σ_H) and minimum (σ_h) horizontal stresses:

$$\sigma_H = 6.5 \text{ MPa} + 0.0374 \text{ MPa/m} \quad (11\text{-}2)$$

$$\sigma_h = 2.5 \text{ MPa} + 0.0255 \text{ MPa/m} \quad (11\text{-}3)$$

The measured vertical stress is on average almost equal to the weight of the overlying strata.

From the large amount of three-dimensional overcoring measurements conducted in the Baltic Shield it is recognised that two of the principal stresses normally are oriented more or less horizontally. Hence, one of the principal stresses is close to vertical.

The azimuth of the maximum horizontal stress in Sweden, as determined from stress measurements, varies both regionally and locally. For the southern and central part of Sweden a trend towards NW-SE orientation is observed. In the northern part of the country, where the picture is even more scattered, a possible N-S trend can be found.

11.2.2 Data from large depths

Stress data from larger depths (>1000 m) within the Baltic Shield are available from four sources only; recent measurements near Oskarshamn, the deep Gravberg-1 borehole, the Kola borehole, and results from fault plane analysis of earthquakes.

During 1996, hydraulic fracturing stress measurements were conducted down to 1340 m below surface (Ljunggren and Klasson, 1997) in the deep borehole KLX02 at Laxemar, near Oskarshamn. Tentative interpretations of these measurements indicate that the increase of stress magnitudes with depth is of the order of 0.02 MPa/m.

In the deep Gravberg borehole breakouts where interpreted for the depth range 1250-3950 m below surface (Stephansson et al., 1989). These breakouts yielded an average orientation of 109° (clockwise from magnetic north) for the maximum horizontal stress.

No direct stress measurements at great depth were carried out in the Gravberg-1 borehole. However, constraints can be put on the minimum horizontal stress by considering leak off tests (Moore and Brittenham, 1990), losses of large quantities of drilling fluid (Vattenfall, 1991), and downward focused hydrofracturing at total depth (Lindbo, 1989). The minimum stress estimate from these tests and events are shown in Figure 11-2. Note that the stress estimates shown in Fgiure 11-2 are from Vattenfall (1990) and are slightly less than those presented in this report.

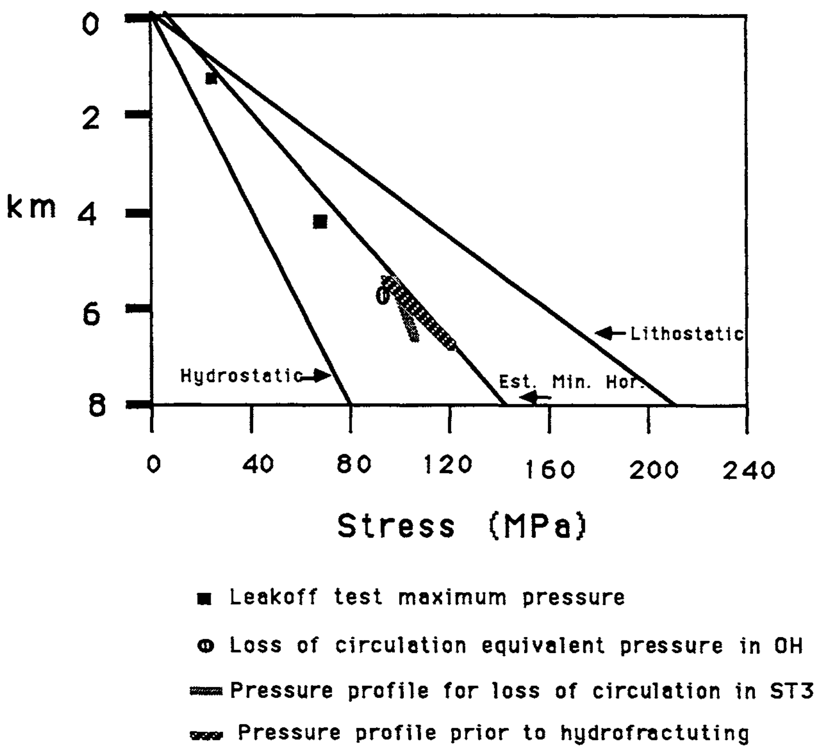


Fig. 11-2. Estimated state of stress in the Gravberg-1 borehole. The points where the formation was actually fractured in sidetrack 3 both during the fluid loss and hydrofracture operation are not known, therefore, a depth range of possible pressures is presented. Stress estimates and figure from Vattenfall (1990).

Breakouts recorded in the superdeep Kola borehole indicate maximum horizontal stress orientations of 110-120° (WNW-ESE) (Vernik and Zoback, 1989). Attempts to estimate stress magnitudes from breakouts yielded values in the range 100-120 MPa for horizontal stresses at 4500 m depth.

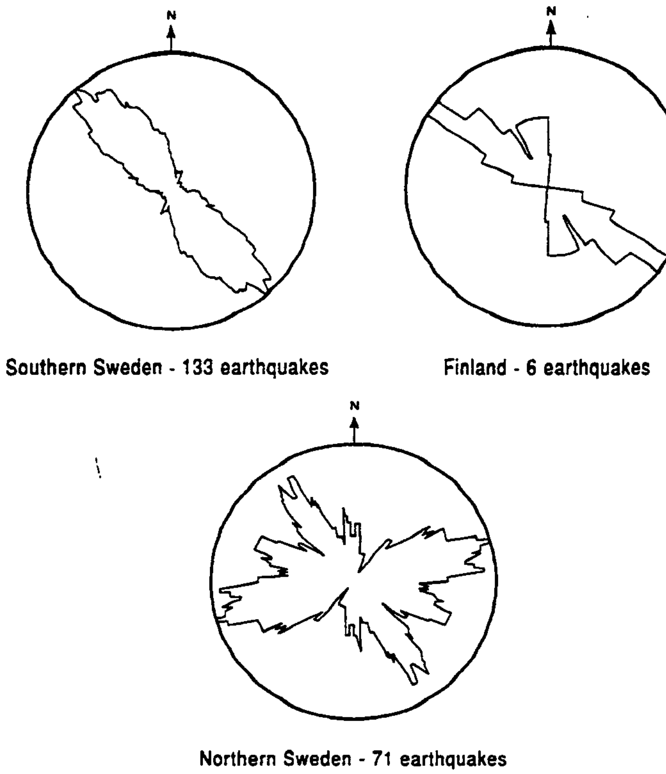


Figure 11-3. Orientation of maximum horizontal compressive stress as determined from earthquakes in the Baltic Shield (Slunga, 1991).

Focal plane solutions for a large number of earthquakes in Sweden (and a few in Finland) ranging in source depth from a few km to 30 km clearly show a NW-SE orientation of the maximum stress in the southern parts of Sweden and in Finland (Figure 11-3). In northern Sweden, directions obtained are much less consistent (Slunga, 1991).

11.2.3 Interpretation

Stress data from deep boreholes in the Baltic Shield and from measurements in crystalline rocks elsewhere in the world are presented in Figures 11-4 and 11-5 (Ljunggren and Leijon, 1996).

It should be noted that data from great depths are sparse. Furthermore, stress measurements at great depth may be assumed to include larger errors than what is normally anticipated. There are no data on stress magnitudes at large depths available from Sweden. The extrapolation lines seen in the figures, referring to Swedish data, are based entirely on measurements down to 1000 m.

Despite these uncertainties, an attempt is made to estimate upper and lower bounds for stress magnitudes. The extrapolation of Swedish shallow data to 5 km depth does, at deeper levels, form an upper bound for all stress data presented in Figures 11-4 and 11-5. From the compilation of deep stress measurements world-wide trends towards unchanged or decreasing stress gradients at large depths are observed. It is thus suggested that the equations for the extrapolation lines based on Swedish data be used as the upper bound for horizontal stress magnitudes. As stress magnitudes in the Baltic Shield tend to be somewhat higher when compared to results from other locations in Europe and elsewhere, a lower bound may be inferred by the envelope of minimum horizontal stresses in Figures 11-4 and 11-5. The vertical stress is assumed to correspond to the weight of the overburden.

With these assumptions, we obtain the following stress bounds:

Upper bound:	Lower bound:	
$\sigma_H = 6.5$ MPa + 0.0374 MPa/m	$\sigma_H = 0.025$ MPa/m	(11-4)
$\sigma_h = 2.5$ MPa + 0,.0255 MPa/m	$\sigma_h = 0.01667$ MPa/m	(11-5)

and

$$\sigma_v = 0.027 \text{ MPa/m} \quad (11\text{-}6)$$

The stress limits according to equations 11-4 to 11-6 are shown in Figure 11-6. Note that the minimum stress level measured in the KTB main borehole at 6 km (Figure 11-4) and that estimated in the Gravberg-1 borehole at 6 km (Figure 11-2) are approximately the same at 110 MPa. This value is somewhat lower than that projectd by the trends in the shallower stress data.

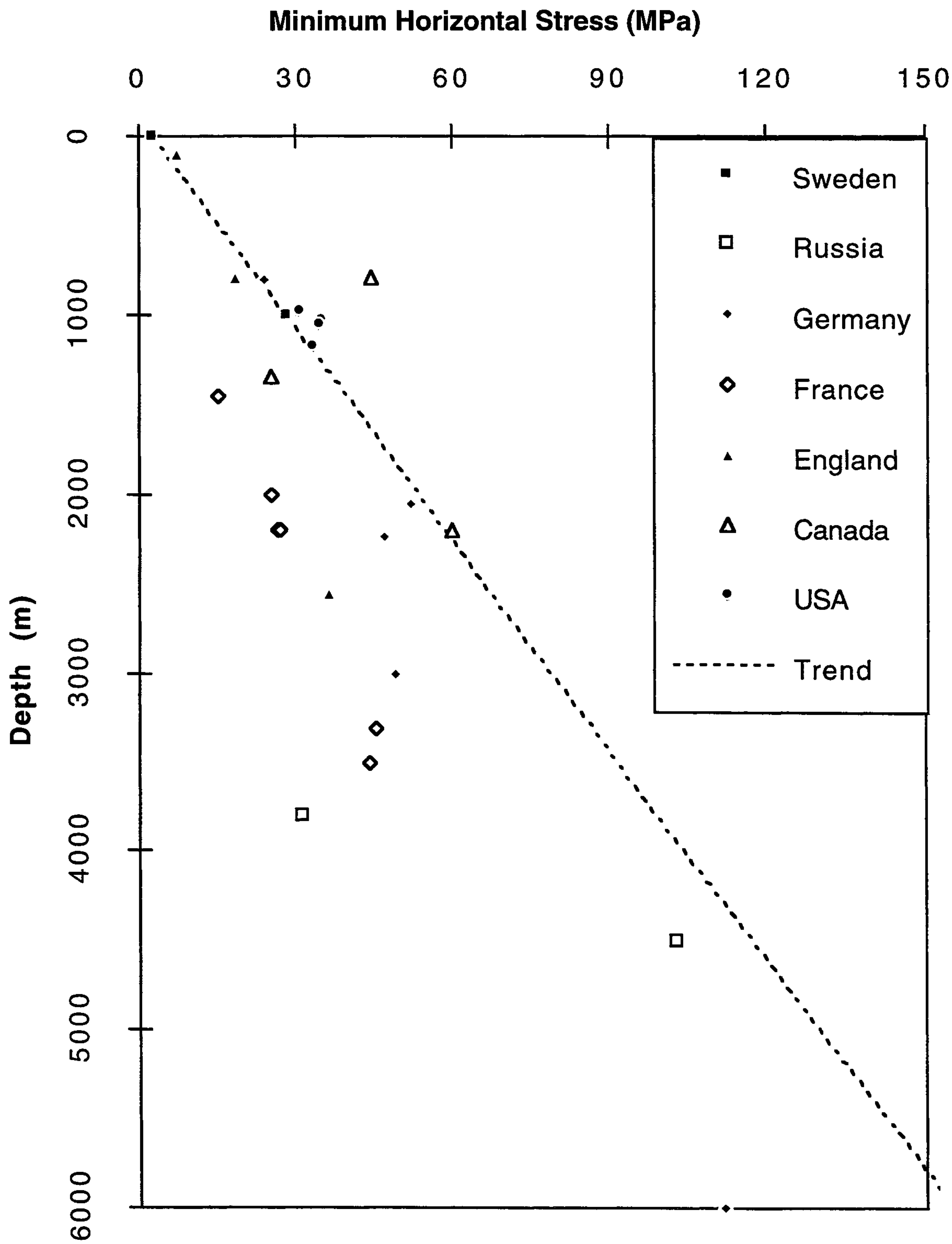


Figure 11-4. Compilation of deep stress data, minimum horizontal stress. The dashed line illustrates the Swedish data extrapolated down to 6 km depth.

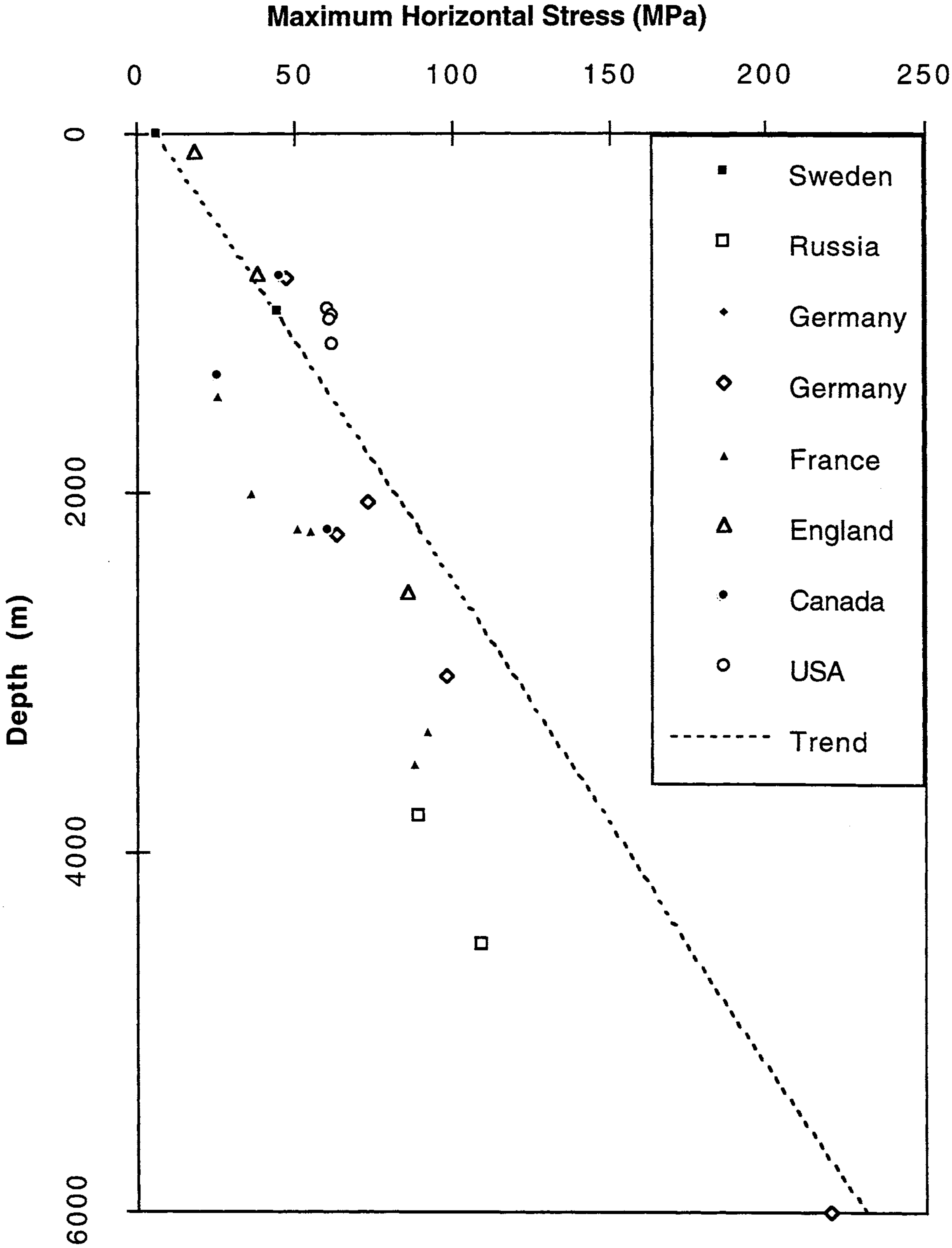


Figure 11-5. Compilation of deep stress data, maximum horizontal stress. The dashed line illustrates Swedish data extrapolated down to 6 km depth.

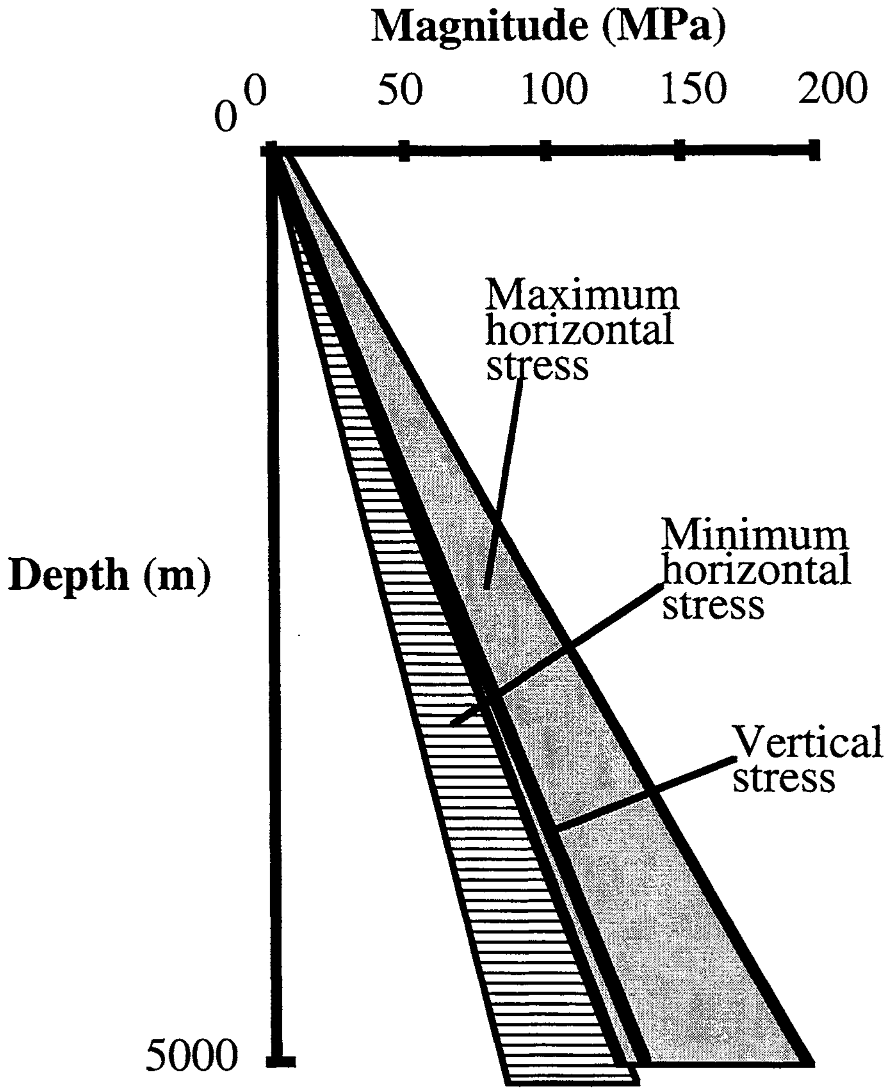


Figure 11-6. Suggested stress limits for stresses in Sweden down to a depth of 5 km.

12 NATURAL SEISMICITY

There is currently a debate on whether earthquakes observed in the Baltic Shield are primarily due to glacial rebound (Muir-Wood, 1993) or plate tectonic stresses (Slunga, 1991). Likewise, there is great debate on what the present strain rate is in the Baltic Shield due to plate tectonic stress. Estimates range from less than 10^{-11}/yr based on geological observations (Muir-Wood, 1995) to values greater than 10^{-8}/yr based on earthquake and micro-earthquake studies (Slunga, 1991). The latter values are supported by geodetic studies in Finland which show strain rates as high as 10^{-7}/yr and horizontal movements on the cm/yr level in some areas (Chen, 1991). Note that these values are based on a complex data set collected over many years and may be error prone (Scherneck et al., 1996). Reprocessing of the data show that some of the calculated strain rates in western Finland may be somewhat lower (Chen, 1992). However, in spite of the uncertainties, there are an indication that the instantaneous horizontal deformation rate in the Baltic Shield may be much higher than previously thought and are supported, in part, by more recent GPS measurements in Sweden (Scherneck et al., 1996).

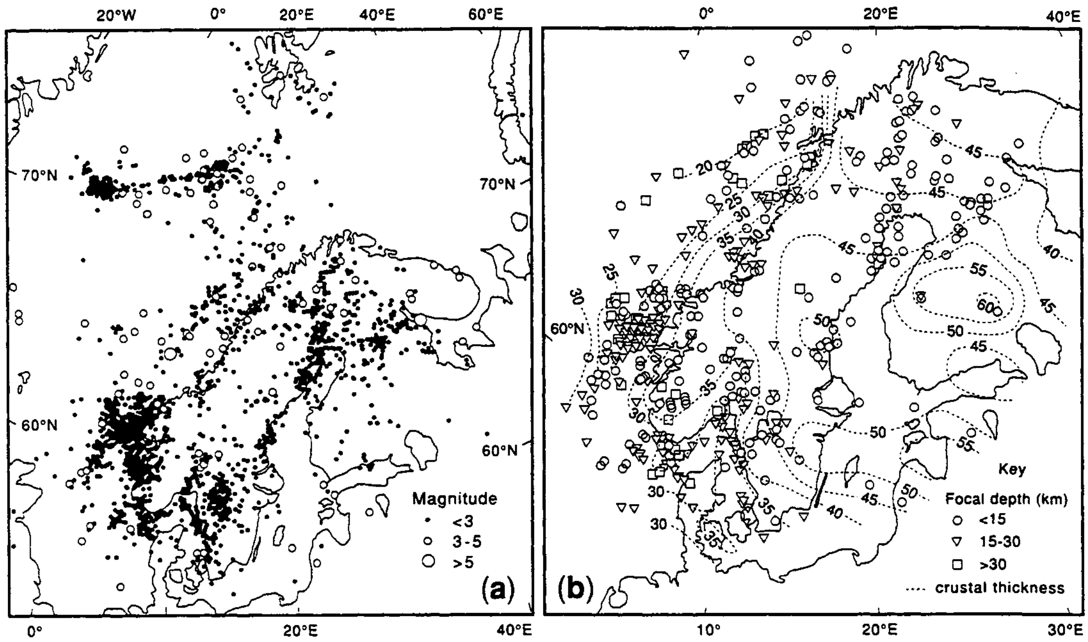


Figure 12-1. Earthquake epicenters in northern Europe during the period 1965-1989. a) Location of earthquakes by magnitude, b) location by depth. After Ahjos and Uski (1992), from Blundell et al. (1992).

12.1 EARTHQUAKE DISTRIBUTION

Extraction of earthquake locations from the Fennoscandian catalog from the time period 1965-1989 shows that present day activity in the Baltic Shield is concentrated towards south-western Norway, south-western Sweden, and along the north-eastern coast of Sweden (Figure 12-1). Earthquake intensity in these areas appears high in Figure 12-1. However, if northern Europe earthquake activity is compared with south-eastern Europe the overall earthquake activity in the Baltic Shield is low (Figure 12-2). Most of the earthquake fault plane solutions in the Baltic Shield indicate a strike-slip stress regime with the maximum horizontal stress in approximately the NW-SE direction (Gregersen et al., 1991; Slunga, 1991). This direction is fairly well defined in southern Sweden, but becomes more scattered towards the north (see Figure 11-2)

12.2 THE ASEISMIC SLIP MODEL

Slunga (1991) presents a model for how faults behave in the Baltic Shield and how present-day earthquakes are related to tectonic stresses. In the model, the Fennoscandian crust consists of several large blocks which are separated by fault zones. Differences in spreading rates at the mid-Atlantic ridge cause a non-uniform stress field to act on these blocks. This results in the blocks sliding and rotating relative to one another. The major assumption in the model is that nearly all of this motion takes place aseismically with only occasional earthquakes due to asperities in the fault zones. Order of magnitude calculations (Slunga, 1991) indicate that the aseismic to seismic slip ratio along fault zones in the Baltic Shield is on the order of 10^5. Calculations along the San Andreas Fault indicate a ratio on the order of 10-100 (Boatwright and Cocco, 1996), considerably less than for the Baltic Shield.

12.3 EXPECTED MOVEMENTS

A constant horizontal strain rate of 10^{-8}/yr distributed over a 100 km wide zone, as assumed by Slunga (1991), would imply the following relative movements between blocks over the indicated time spans:

1000 years	1 m
10000 years	10 m
1 Ma	1 km
50 Ma	50 km

Detecting 10 metres of relative movement over a 100 km wide zone in the geological record is probably not possible. However, movements of a few kms should be fairly easily observed and are not. This shows that an average horizontal strain rate of 10^{-8}/yr over the last 50 Ma (since the opening of the Atlantic) is unreasonable and an average horizontal strain rate of 10^{-11}/yr as indicated by movements in the surrounding margins is more likely (Muir-Wood, 1995). However, these calculations are only valid for average strain rates. The instantaneous strain rates could be much higher and it is possible to conceive of a model where the relative movement reverses direction resulting in an average strain rate over long time periods to be much lower than the short period strain rates. Such a model would reconcile the geological evidence of low strain rates measured over long periods of time with the geodetic and seismological evidence for high strain rates over short periods of time.

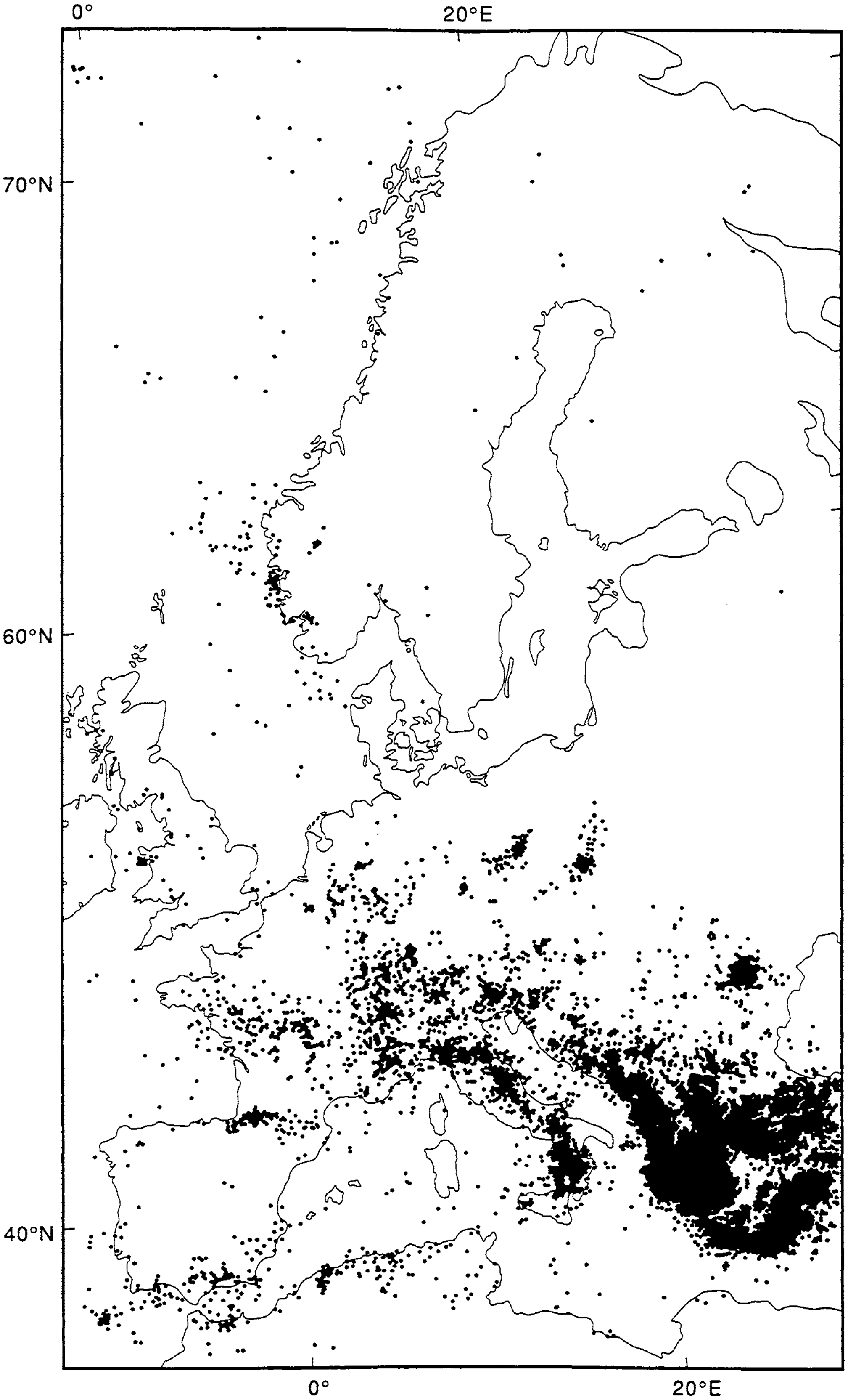


Figure 12-2. Earthquake epicenters in Europe showing historical earthquakes with magnitude >7 from 1897 onwards and instrumental earthquakes with magnitude >4 from 1960 onwards. After Simkim et al., (1989), from Blundell et al. (1992).

Although the strain rates may be high over short periods of time, this does not imply that the high horizontal strain rates are due to tectonic stress. They could also be due to glacial rebound. Modelling calculations of the average horizontal strain rate due to glacial rebound are on the order of 10^{-9}/yr (Gasperini et al., 1991), lower than that indicated by the geodetic and seismological data. However, this is an average strain rate based on 1D modelling. If the influence of crustal thickness, heat flow, topography, ice cap thickness and that the movement is probably concentrated in discrete zones, much larger values for strain rate at certain locations would probably be calculated.

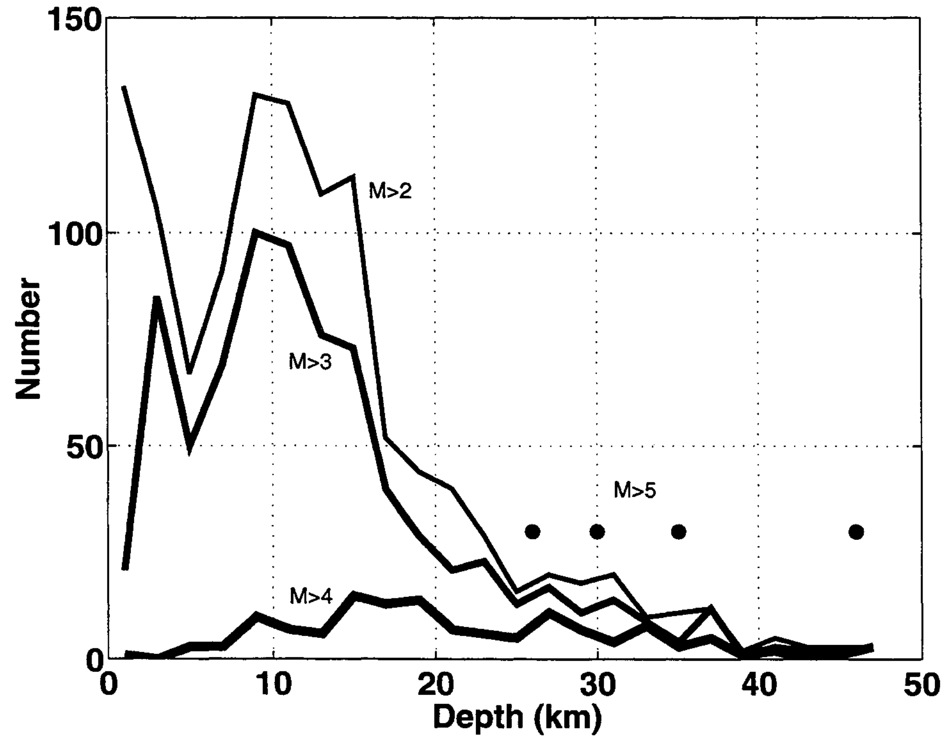


Figure 12-3. Depth distribution (for those earthquakes where the depth could be determined) for crustal earthquakes for the time period 1375 to 1990 for magnitudes greater than 2, 3, 4, and 5. The four magnitude 5 earthquakes are plotted as filled circles at the depths at which they occurred. Note that the two deepest M>5 earthquakes are estimated from macro-seismic observations (pre-1904). Pre-1904 estimates account for about 20% of the depth estimates in the figure. Data are taken from the EGT database (Blundell et al., 1992).

12.4 SHALLOW EARTHQUAKES

Two inventories of shallow (focal depths less than 5 km) earthquakes in Sweden have been made (Sundqvist, 1995; Wahlström, 1980). A total of 18 shallow earthquakes were identified in Sweden during the time period 1967-92. Most of the events had magnitude in the range of 2 to 3. The majority of these events were located in south-western Sweden or along the east coast of central Sweden. Note the major portion of the shallow events recorded in south-western Sweden was during the time period that the FOA network was active there (1979-1984). Sundqvist (1995) also points out that numerous local events are recorded by the Swedish Seismograph Station Network (SSSN) that show Rayleigh waves (an indication that the source is shallow), but that the magnitude of these events are too weak for them to be recorded on more than one station and cannot, therefore, be located.

Inspection of the depth distribution curves for earthquakes (Figure 12-3) shows that the higher magnitude earthquakes are concentrated towards the deeper crust. The detection threshold for Sweden is about magnitude 2.7 (Muir-Wood, 1993). If this threshold was lower there would probably be a greater difference between the magnitude 2 and 3 curves in Figure 12-3 at shallower levels. However, even with this lack of coverage, the majority of recorded and historical earthquakes occurring shallower than 5 km have a magnitude less than 3, whereas the majority occurring in the depth interval 5 to 15 km have a magnitude of between 3 and 4. The observation that the stronger earthquakes occur deeper in the crust indicates the difference between the minimum and maximum horizontal stresses continues to increase with depth, even below 5 km, in the Baltic Shield.

13 FLUID COMPOSITION AND BACTERIA

13.1 BACKGROUND

In a crystalline bedrock environment, recharge groundwaters initially react with the overburden (if present) and subsequently with the fracture surfaces during percolation through the bedrock to greater depths. Normal water/rock geochemical evolution during percolation results in groundwaters becoming more alkaline and increasing in dissolved salt content (TDS) with increasing depth, in particular accommodating greater amounts of sodium and/or calcium, chloride and sometimes sulphate.

The accumulated amounts of TDS very much depends on the groundwater flowrate through the rock, i.e. the greater the flowrate the less water/rock reaction time and the lower the TDS. Fresh to brackish groundwaters therefore tend to characterise the upper approximate 500 m or so, where groundwater flow is driven by head differences based on topographical variations and where there is a greater number of conducting fractures. Groundwater mixing from different sources may also contribute to changing hydrochemical properties. Approaching 1000 m depth groundwater flow conditions usually change; flowrates are less active and tend to be associated with more discrete, isolated water-conducting fracture systems. In this environment groundwaters are often more saline in character due to increased rock/water interaction. These waters, however, are still to some extent influenced by surface-derived input components under favourable hydraulic conditions. For example, in the case of Fennoscandia from recent precipitation, ancient and modern marine waters (i.e. coastal localities) and cold climate waters (e.g. glacial melt waters).

Mostly as a result of mining activities in the Canadian Shield and deep exploration drilling in the Fennoscandian Shield, saline waters (TDS 10000-100000 mg/L) and brines (TDS > 100000 mg/L), are found to be relatively commonplace at depths greater than 1000 m (Figure 13-1). Many of these brines are Ca-Na-Cl in type with a Ca:Na ratio of around 1.5-3.0 (e.g. Gravberg between 5453-6967 m has a value of 3) and some are extreme in composition, containing up to 6 g/L Ca, 5 g/L Na and 20 g/L Cl in the Canadian basement at depths of 1500 m (see compilation by Smellie,1996). In some cases (e.g. Äspö, Sweden) the Ca:Na ratio is nearer one, and in other cases (e.g. Olkiluoto, Finland) slightly less than one. Increased amounts of Na are considered to reflect water/rock interaction with more heterogeneous bedrock types than granitic varieties, for example the presence of Na-rich amphibolite units.

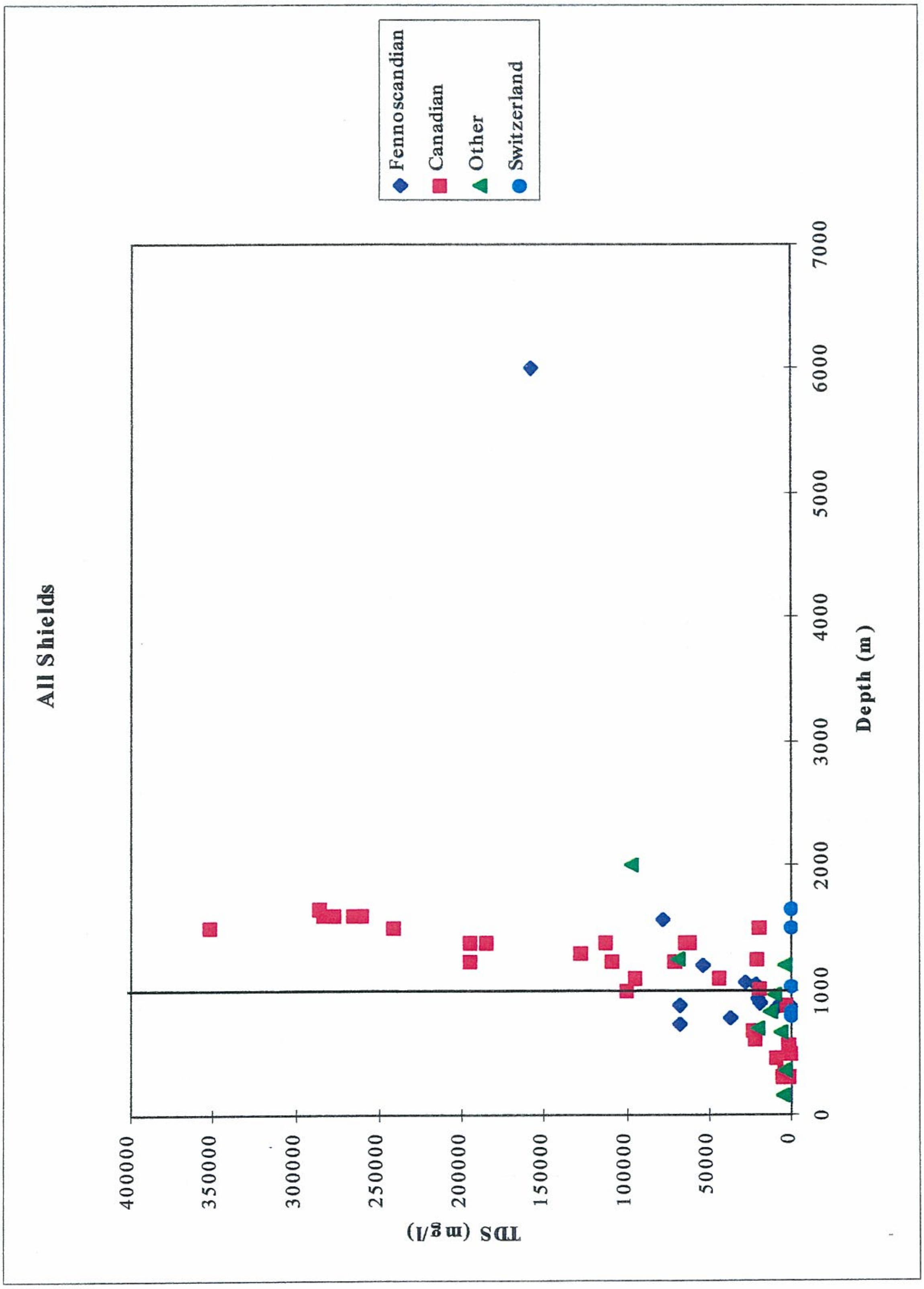


Figure 13-1. Compilation of TDS concentrations in crystalline rock down to 6 km depth from all areas reviewed.

13.2 ORIGIN OF THE BRINES

The origin of saline groundwaters have recently been reviewed (e.g. Lampén, 1992; Raven and Clark, 1993). To explain the occurrence of saline waters several questions need to be answered. What is the origin of the salinity? Was it introduced into the bedrock (e.g. marine-derived waters), does it represent relict, ancient fluids in the bedrock (e.g. metamorphic fluids), does it derive from bedrock reactions with meteoric-derived waters, and what role does bedrock geochemistry play in determining the groundwater chemistry? Furthermore, what is the mean groundwater residence time, and how old are the saline waters?

As summarised by Lampén (1992), the main mechanisms whereby saline constituents can be introduced into the Fennoscandian Shield groundwater system are via:

1) Palaeozoic basinal brines which have undergone metamorphism and extensive interaction with the bedrock
2) Palaeozoic sea water which has undergone chemical alteration during surface evaporation followed by extensive interaction with the bedrock
3) Dissolution of Palaeozoic evaporates followed by infiltration into the bedrock
4) Proterozoic sea water or basinal brines
5) Holocene brackish water

Recently the concept of sea water freezing has been forwarded to explain the Ca-rich brines common to both Canada and Fennoscandia (Herut et al., 1990). The freezing model does not by itself account for the high Ca:Mg ratios found in natural brines, as neither Ca nor Mg are directly involved in the sequence of mineral precipitation during freezing. However during migration into the subsurface bedrock, rock/water modifications take place which influence the Ca:Mg ratios but leave the Na:Cl ratios intact. This hypothesis is debatable; it may be only local in extent.

Local salinity sources from within the bedrock include:

1) Hydrolysis of silicate minerals
2) Release of salts from the rupture of fluid inclusions
3) Radiolytic decomposition of groundwater

It is generally accepted, however, that no one process or source can account for the observed salinities in the basement shield areas; most reported samples seem to represent mixtures of meteoric water with a highly concentrated brine (Pearson, 1987), which may be an ancient relict sea water or fluids genetically linked to geochemical processes occurring from rock/water interactions over long periods of geological time in the bedrock.

As pointed out by Raven and Clark (1993), groundwater hydrochemical and isotopic data show the basement brines to be highly modified by low temperature alteration such that many of the primary chemical and isotopic signatures (e.g. stable isotopes) have been lost, thus making it impossible to differentiate whether the brines are meteoric in origin or syngenetic with the rocks themselves. An exception are the strontium isotopes which support a large-scale in situ water/rock origin for most of the cations. The solutes in the brines may thus be as old as the rocks themselves, giving ages of 10^6 to 10^9 years for the most concentrated brines.

Further support for a bedrock origin has recently been shown from the Underground Rock Laboratory (URL) at Whiteshell, Manitoba (Gascoyne et al., 1996). At this site, long-term, in situ experiments (4-5 years) carried out in boreholes drilled into bedrock of low hydraulic conductivity, have revealed a close similarity in chemical composition between sampled pore/fissure fluids and deep brines.

An interesting and highly relevant conclusion from studies of deep mines in the Canadian Shield is that there is no clear correlation between major rock type and the groundwater chemistry. "In all cases, the brines and brackish groundwater are dominated by a Ca-Na-Cl facies, with similar maximum concentrations of specific species in the most concentrated brines" (Raven and Clark, 1993). This essentially indicates that if the chemistry of the saline groundwaters is known from one region, the location of a repository in another basement region would be subject to similar groundwater types, thus precluding extensive hydrogeochemical investigations at depth.

Fennoscandian data show many similarities with the Canadian Shield regions; they indicate a high degree of evolution over very long time scales, at least in the range of 1 Ma as shown by ^{36}Cl studies at Laxemar (Louvat et al., 1997).

13.3 GAS CONTENTS IN DEEP GROUNDWATERS

The presence of deep gases from the Shield regions (from boreholes and underground mine workings) has been used to help understand the origin of the saline groundwaters. In particular, the presence of methane enables isotopic determination of $\delta^{13}C$ which can help to distinguish between a biogenic ($\delta^{13}C$ < -50 ppt) and a thermal or abiogenic ($\delta^{13}C$ > -50 ppt) origin. Methane is ubiquitous in crystalline basement rocks and has been the focus of considerable study in Canada (Fritz and Frape, 1987) and in Sweden (e.g. Gravberg; Jeffrey, 1990). It is commonly found in highly variable amounts in association with nitrogen (to 80%), He (to 50%), Ar (to 4%), and traces of other hydrocarbons; sometimes hydrogen is also present in considerable amounts.

The deep basement methane gas, both isotopically and compositionally, support an abiogenic origin. The Canadian Shield methanes may partly be a result of high temperature reactions involving an inorganic carbon source (i.e. CO_2; graphite) with the participation of reduced iron or hydrogen (Welhan, 1987). By association, this also supports a deep bedrock origin for the saline groundwaters with little significant input from near-surface derived waters which might be expected to contain methane of biogenic origin.

At Laxemar, Sweden, the uniqueness of the deep saline groundwaters warranted the use of less frequently measured noble gases such as ^{3}He, ^{4}He, ^{37}Ar, ^{39}Ar, ^{40}Ar, ^{85}Kr and even ^{81}Kr. Although not all data are available, initial results point to very large quantities of ^{4}He (~10^{-2} cc/cc) and an extreme $^{40}Ar/^{36}Ar$ ratio (^{40}Ar is enriched from feldspar breakdown by at least four times, compared to atmospheric) at the deepest sampled level (1420 m). Collectively, this supports long residence times (i.e. stagnant character) of the saline groundwaters and the potential importance of water/rock reactions in interpreting their composition (Smellie et al., 1995).

The accumulation of such large volumes of helium (and other examples cite hydrogen and methane) suggests that upward diffusion is sometimes restricted deep in the bedrock resulting in a potential build-up of pressure. In most cases this may simply reflect the enormous overpressures at great depth, coupled with low permeabilities. There are examples from deep mines in the Canadian Shield of sudden violent releases of pressure during exploratory drilling from deep gallery locations (S.K. Frape, per. comm., 1996).

13.4 BACTERIA

Some 50 years ago, it was assumed that microbial life would only exist in the uppermost metres of both terrestrial and marine environments. Since then it has been shown that microbes can survive to the floors of the deepest seas and also deep into the Earth's crust. The presence of bacteria in crystalline bedrock in the deep subterranean biosphere (> 100 m) is well documented in the literature (e.g. in Sweden, Pedersen and Ekendahl, 1990; Pedersen and Ekendahl, 1992a; Pedersen and Ekendahl, 1992b). The nutrients (i.e. organic material) were considered to be near-surface derived and transported to depth by the groundwater flow system. More recently, however, studies have shown that not only do bacteria exist at even greater depths, at least down to 1500 m and more in crystalline bedrock, but they survive independent of photosynthetic processes, neither requiring organic matter nor oxygen for their existence (Kaiser, 1995). High levels of hydrogen and biogenic methane sampled deep in basalts suggested an active methanogenic community, whereupon anaerobic organisms use hydrogen as an energy source (derived from the reaction of Fe(III) in the rock with groundwater) to convert dissolved carbon dioxide to biomass, releasing methane as a by-product.

The significance of bacteria surviving at great depth, independent of the biosphere, and able to produce large quantities of methane, may mean that previous interpretations of deep groundwater evolution may have to be somewhat modified.

14 INTEGRATED GEOSCIENTIFIC MODEL TO 5000 M DEPTH

14.1 CONCEPTUAL MODEL

From the review of available data and its integration a conceptual model has been developed for the upper 5 km of crust in Sweden. In general, the upper c. 1 km of the crust appears to have more open fractures throughout the shield area and consequently the hydraulic conductivity can be expected to be higher. The increased amount of open fractures in the upper 1 km or so does not appear to be limited to the Baltic Shield. Similar features are expected to be found throughout Europe and even on the Arabian Shield, although the thickness and intensity of fracturing may vary. Below c. 1 km the crust is still fractured, but the frequency of open hydraulically conductive fractures is lower and the distance between fracture zones is greater (Figure 14-1). The upper 1 km is not only characterised by increased vertical to sub-vertical open fracture sets, but also regular open sub-horizontal fractures and fracture zones which further facilitate groundwater circulation and mixing. This assumption of enhanced porosity is based primarily on geophysical evidence, but also on the hydrogeological data. Note that geological data from deep boreholes generally do not discriminate between hydraulically open and sealed fractures. This lack of discrimination implies that the proposed increase in open fractures at shallow levels (principally reactivated pre-existing sealed fractures) is masked by the numerous amount of sealed fractures in borehole data.

Although the higher degree of open fracturing and increased permeability in the upper c. 1 km may be relatively universal, the hydrochemistry may differ drastically depending upon the geographical location. For this reason two models for the upper 5 km of crust in Sweden have been developed, one for southern Sweden where the influence of topography is minor, and one for central/northern Sweden where topography plays a major role. The southern model is similar to the one derived by Nurmi et al. (1988) whereas the central/northern profile differs in that the Caledonide mountain belt provides significant hydraulic head to drive meteoric water deep (5-10 km) into the crust (see Torgersen (1990) for a conceptual overview). The flow of this water at depth is confined to a limited number of conductive fracture zones.

Natural lateral temperature gradients exist in the Swedish bedrock due to lateral variations in heat production and thermal conductivity. However these are relatively minor and generate only insignificant pressure gradients for groundwater circulation compared to the topographic effects.

Below a depth of c. 1 km in southern Sweden and anywhere from 1 to 10 km further north, it is suggested there always exists highly saline water or brine (Ca-Na-Cl) that can be considered to have been near-stagnant for long periods of time (hundreds of thousands to several million years). This brine mainly developed by in-situ rock water interactions. Strong support for the long residence time of this water is found in the high concentrations of ^{4}He in the deep waters from the Gravberg-1 and Laxemar boreholes. The concentrations in Gravberg-1 indicate the water has been stagnant on the order of 100s of millions of years (Juhlin et al., 1991) and ^{36}Cl isotopic data from the deepest (>1000 m) Laxemar locations indicate residence times in excess of one million years (Louvat et al., 1997). This brine is encountered first at a depth of about 6 km in the Gravberg-1 borehole and at about 1 km at Laxemar.

The large scale stability of the rock mass at depth is governed by the existing stress field, the presence and characteristics of fractures or fracture zones and seismic activity. In the conceptual model the rock stresses increase with depth and it is further suggested that the absolute stress anisotropy will reduce at depths first greater than 5-10 km.

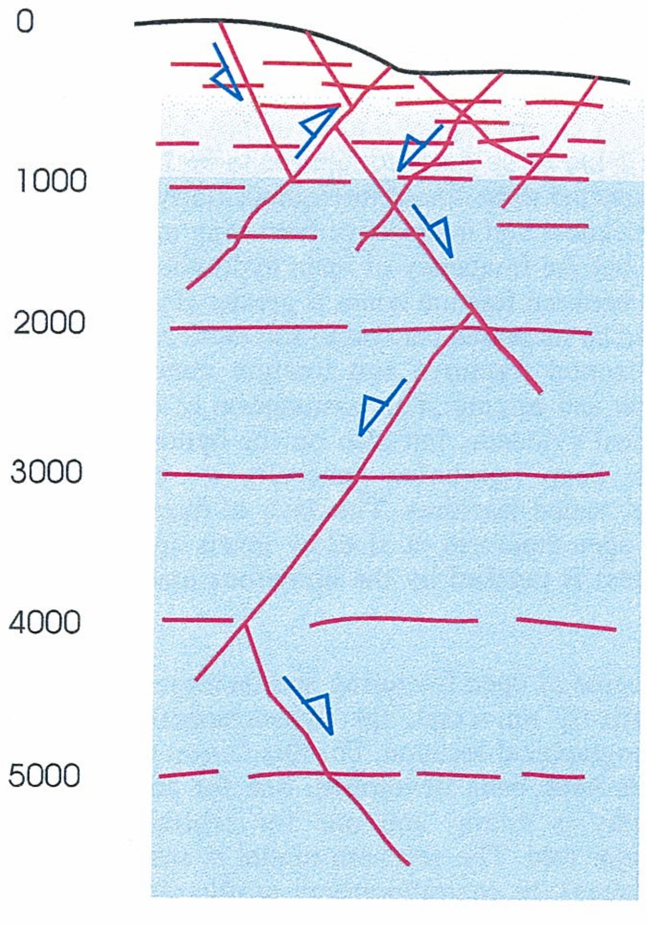


Figure 14-1. Conceptual model for fracturing in the upper crust in Sweden. The upper 1 km is highly fractured (especially the upper 300 m) and is highly permeable compared to depths greater than 1 km where permeability is confined to more discrete fracture zones. The darker the shading the greater the salinity of the water.

In a simplified approach, the rock mass can be divided into homogeneous, large rock blocks surrounded by fracture zones. The rock blocks consist of the intact matrix and a fracture system. The fractures zones bound the rock blocks and constitute zones of weakness where properties such as strength and deformability differ significantly from that of the rock blocks. Consequently, these zones provide an efficient buffer to rock movement triggered, for example, by earthquake activity.

The present stress field in Sweden, with a NW-SE trend of the maximum horizontal compression in southern and central Sweden, is mainly generated by gravitational and plate tectonic forces. The near-surface seismic activity is small (Sundqvist, 1995). Typical magnitudes in Sweden of these events are less than 3 on the Richter scale.

The general hydrogeological conditions in southern Sweden are similar to those shown schematically in Figure 14-1 where the upper c. 1 km is more fractured and has higher permeability. Although the topography is minor, it still gives rise to pressure differences which cause groundwater flow. Large surface water reservoirs, such as Lake Vänern and Lake Vättern, may also have considerable influence on the lateral extent of th eflow systems. In the conceptual model, the flow consists of meteoric water penetrating down to c. 1 km depth in the interior of the country (e.g. lowland areas of Figure 14-2). Towards the coast the penetration is shallower and the groundwater composition is influenced by the present day brackish Baltic Sea and relict saline water of the Litorina Sea. Due to the decreased fracturing and low pressure gradients the meteoric water does not generally circulate to depths below c. 1 km in southern Sweden. However, there may be fracture zones which facilitate penetration of meteoric water to depths greater than 1 km. Topographic highs, such as the Southern Swedish Highlands, act as recharge areas on a regional scale and can be expected to significantly influence the groundwater flow directions at more shallow depths.

Further north and west in Sweden, the topography of the Caledonides greatly influences the meteoric water circulation pattern (Figure 14-2). Even here surface reservoirs may have some influence on the groundwater circulation pattern. In the Gravberg-1 borehole, relatively fresh water is found to depths of 5-6 km; below this depth the water becomes highly saline. Further towards the west, with greater topography and increased hydraulic heads, it is expected that meteoric water circulates even deeper than in the Siljan Ring area. Towards the coast the depth to the brine becomes shallower as the topographic driving force dissipates and the hydrogeological conditions become similar to those of southern Sweden.

The main difference between the central/northern profile and the southern profile is the depth of meteoric water circulation. Meteoric here implies water which has relatively recently been in contact with the atmosphere. The deep brines may originally have been meteoric water, but they have been stagnant so long that the meteoric signature has been lost. This meteoric circulation is much deeper in central/northern Sweden than in the south. Other parameters such as the thickness of the upper fractured layer, temperature gradient and rock stress are roughly similar on both profiles.

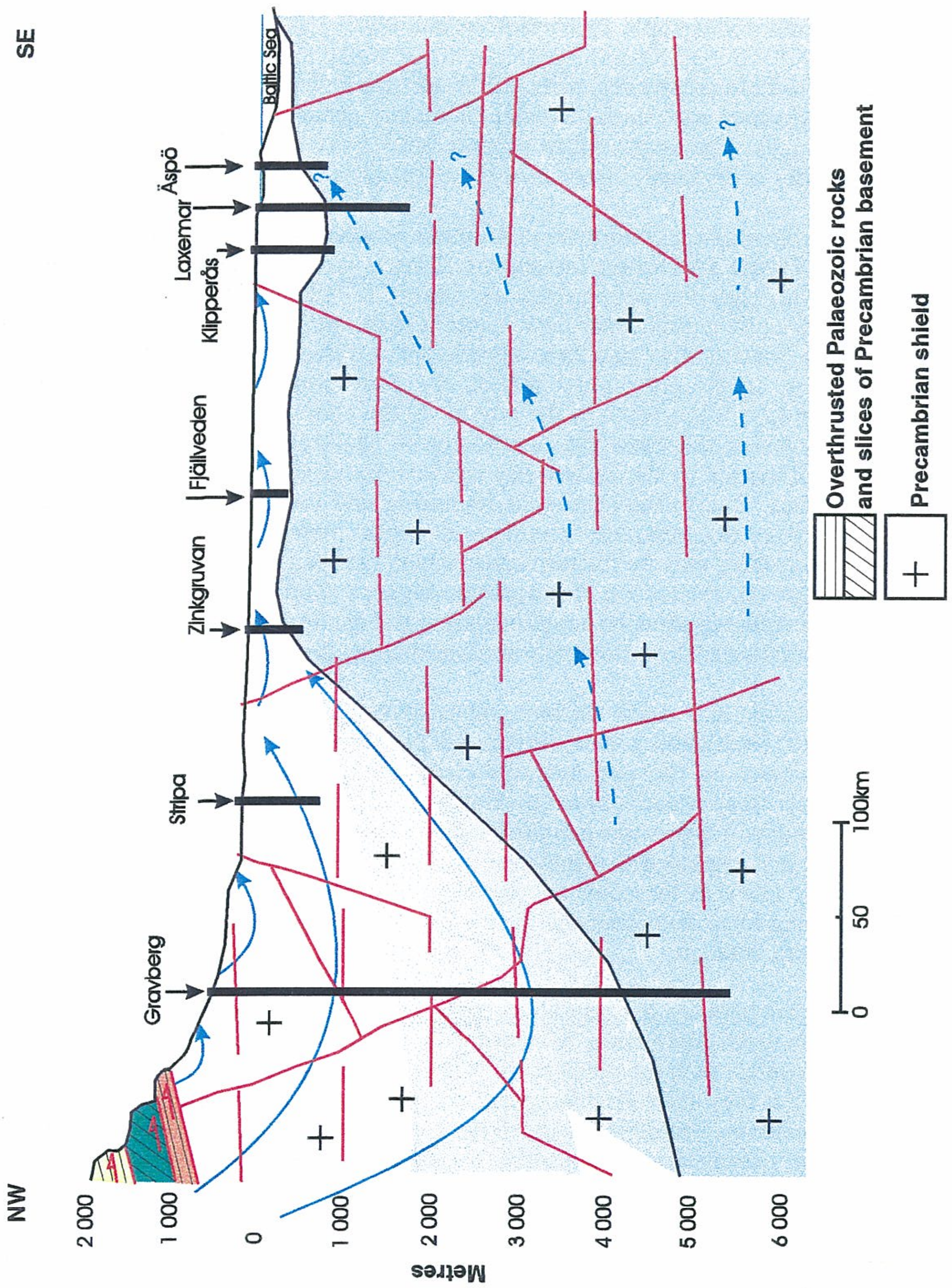


Figure 14-2. Conceptual model for water circulation patterns along a central/northern profile across Sweden. The darker the shading the greater the salinity of the water. Meteoric water is driven deep into the crust by the hydraulic head in the mountains. The fracturing in the uppermost 1 km is the same as that shown in Figure 14-1, but is not shown here for simplicity. This model is partly based on earlier work by Laaksoharja et al. (1993).

14.2 JUSTIFICATION OF MODEL

The data available emphasise the structural and lithological heterogeneity of the crust. This fact entails difficulties in predictions of the deep geology. Only within intrusive bodies like granitoids are the geological conditions so homogeneous and persistent in three dimensions that the geology at depth can reasonably be predicted.

It is primarily surface geophysical studies and borehole data that show the upper c. 1 km of the Baltic Shield to be more fractured than the rock below. The surface geophysical data consist mainly of refraction seismic profiles and surface wave dispersion studies. These methods are rather robust and show a consistent pattern of rapidly increasing seismic velocities in the upper c. 1 km and then a more gentle increase with depth below this level. As mentioned in Båth (1985) and in this report, these observations have also been made on other shield areas. The boreholes presented in this report (Gravberg-1 and KLX02 in Sweden, the Böttstein borehole in Switzerland and the RH12 borehole in south-western England) all tend to show more fractured rock in the upper c. 1 km which is manifested by more rapid and greater intensity variations in the P-wave sonic velocity. All these boreholes have been drilled in granitic rocks. The trend in RH12 is the weakest, with the difference between the amount of fracturing above and below 1 km being less than in the other boreholes.

Logs from non-granitic mining areas in Canada (Juhlin, 1996) do not show an obvious change in character below 1 km compared to shallower levels. This is an indication that caution should be used in generalising the results for the entire Baltic Shield. However, mining areas are anomalies in themselves and the data from the Canadian boreholes need to be analysed in more detail before any long ranging conclusions can be drawn.

A relevant borehole which has not been given much consideration in this report is the Kola borehole (SG-3). This is primarily due to the lack of availability of raw data to examine. The geophysical logs shown in the NEDRA report (NEDRA, 1992) are averaged on too long of a scale to make any visual assessment as to their variability as a function of depth. The same is true for the Krivoy Rog borehole (SG-8) on the Ukrainian Shield where no geophysical log data are presented for the upper 800-900 m. It should be noted that in both of these boreholes the upper 5 km consists of metamorphosed sediments and volcanic rocks where the lithology greatly affects the log response. The sites of the boreholes are also, in part, based on the mining potential of the areas. To assess changes in geophysical properties in the two areas would require access to the Russian raw data. Although we cannot quantitatively evaluate the two boreholes, the NEDRA report classifies several hydrogeological zones or levels in the two areas. At Kola, the upper 800 m contains meteoric water while at Krivoy Rog the meteoric circulation is down to 1500 m.

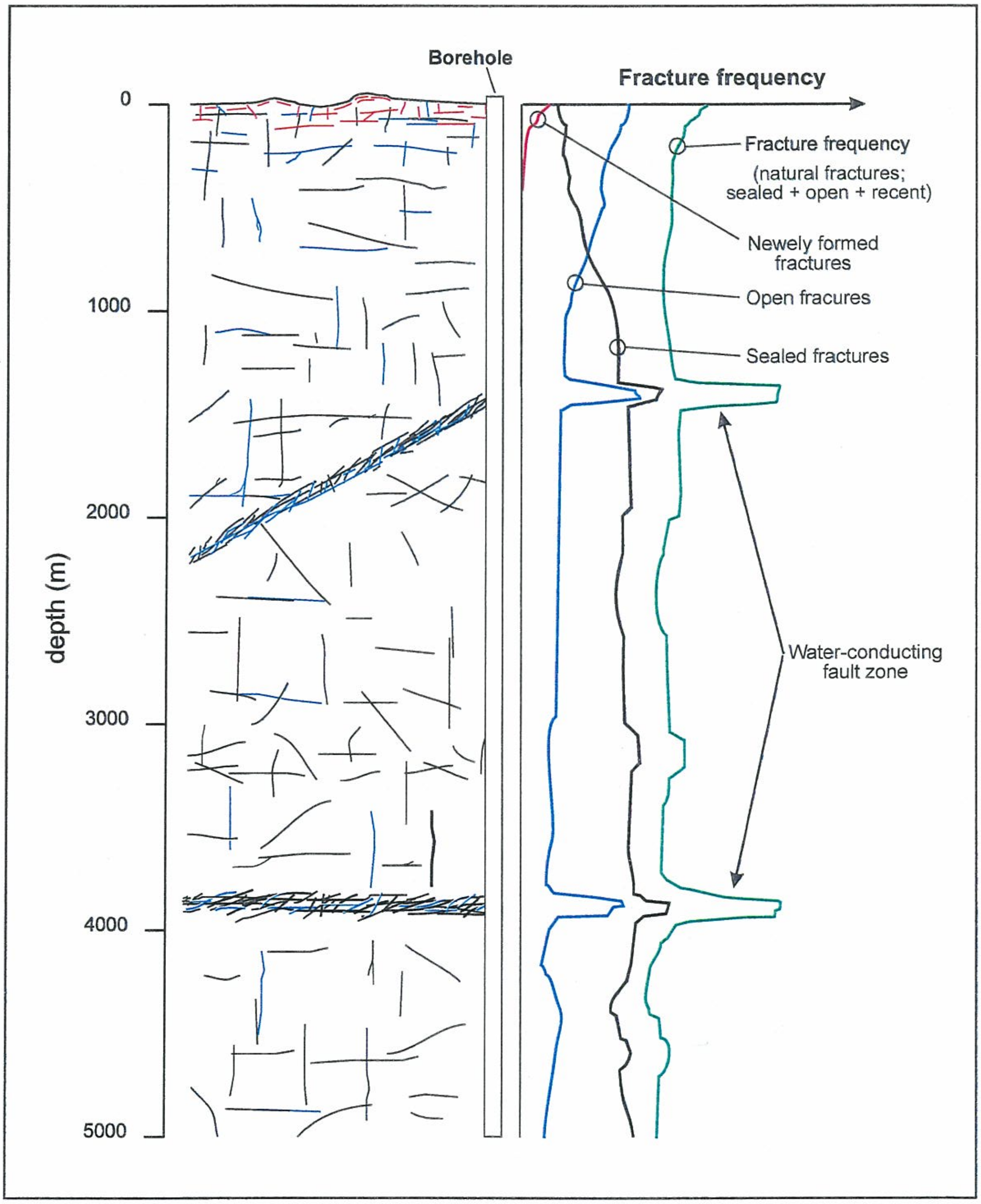


Figure 14-3. Proposed fracture distribution as a function of depth. Recently opened fractures are inferred to be Holocene in age.

Geological compilations do not show an obvious correlation between fracture frequency and depth. Thus, the higher degree of fracturing within the upper c. 1 km suggested in our conceptual models cannot be fully justified by geological information. The reason for the discrepancy between the geological data and the geophysical data is probably due to that geological mapping of fractures in most cases does not distinguish between open and healed fractures. The degree of open and hydraulically active fractures closer to the surface may therefore be higher than at greater depth, notwithstanding the apparent uniform distribution of fractures versus depth (Figure 14-3).

The hydrogeological data shown in Figures 10-1 and 10-2 suggest a decreasing rock mass permeability over the depth range 1000 to 5000 m. The largest values measured at 1000 m depth are about three orders of magnitude in excess of those observed at 5000 m depth. Such a decrease in permeability, although not verified by a sufficiently large number of in-situ measurements to be considered certain, can be explained by a combination of a decrease in fracture frequency and an increase in stress with increasing depth.

From the existing data on rock stresses in Sweden (Figures 11-3 and 11-4) it can be seen that there exists a more or less continuous increase in stress with depth. Although not finally evaluated, preliminary results from hydraulic fracturing in the KLX02 borehole at Laxemar show a continuous increase in the normal stress across opened fractures down to 1340 m, supporting this suggestion. This increase strongly suggests that the strength and deformability characteristics are at least constant or increase with depth.

Although not seen from the results in Figures 11-3 and 11-4 it is also suggested that the anisotropy in the stress field within the uppermost 5-10 km of the crust, will become less at greater depth. Support for this can be obtained from seismic activity in the crust, where most of the earthquakes occur in the upper 20 km, whereas the lower crust is essentially aseismic (Muir-Wood, 1993; Sundqvist, 1995). However, note that the largest earthquakes (M>5) recorded in the Baltic Shield are apparently from depths of below 20 km.

Stress measurements down to 1 km depth suggest a NW-SE trend in the southern part of Sweden for the orientation of the maximum horizontal stress, whereas more scattered orientations are obtained in northern Sweden (Ljunggren and Persson, 1995). A similar picture of the orientation is obtained when studying the maximum horizontal compressive stress released in earthquakes (Slunga, 1991).

Tests of rock strength and deformability parameters on cores from great depths do not reveal very much information on the actual conditions at depths as testing normally is done on intact specimens, free from fractures. Changes in the intact matrix can of course be recognised, but from a stability point of view this is of less interest as such problems are not caused by the intact parts but rather due to existing weakness features.

It is clear from a great number of rock mechanical laboratory experiments on rock fractures that the effective stress increase that can be expected over the depth range considered in this study implies, in general, a considerable reduction in hydraulic fracture aperture and hence in permeability. Thus, for fractures having identical properties we can expect that those at lower normal stress will be more permeable than those at higher stress. However, many factors govern the hydraulic properties of single fractures, such as variations in fracture surface topography and degree of mineralisation. For instance, laboratory tests (Durham and Bonner, 1994) were carried out on mated and unmated fractures where the confining stresses were increased up to a level corresponding to mid-crustal depths. The loading of the mated fractures resulted in a decrease in permeability of 5 to 6 orders of magnitude, whereas the unmated fractures showed insignificant changes in permeability. From this we can draw the conclusion that fractures can stay relatively open also at great depth, which is in accordance with the observations in many of the deep boreholes studied.

Barton et al. (1994) have presented an interesting study of the relationship between in-situ stress and fluid flow in three deep boreholes located in the USA. By using detailed data on fracture geometry from borehole televiewer logging, in-situ stress magnitude and orientation, and precision temperature measurements indicating localised fluid flow, they calculated the stresses acting on each single fracture in the boreholes. Plotting of the stress data for all fractures in Mohr diagrams revealed that most of the hydraulically conductive fractures (70-80%) appeared to be in a critical state of stress with respect to shearing. A great number of laboratory and in-situ experimental studies have shown that small shear displacements along fractures may result in increases in permeability. However, the extent to which shear dilatancy can cause critically stressed faults and fractures to maintain permeability is still poorly understood.

In summary, at great depth the most significant fluid conductors are likely to be fracture or fault zones. Locally these zones may have transmissivities of the same order as major flowing zones closer to the surface. Nonetheless, in terms of bulk values of rock mass permeability we suggest a model with a decrease with depth over the depth range considered in this study. The state of stress solely cannot be used for predictions of flowing features or major flow directions. On a larger scale, the connectivity of fractures and fracture zones is of major importance for the development of anisotropy in permeability.

The conceptual models presented in Figures 14-1 and 14-2 are largely justified by the hydrochemical signatures (Smellie, 1996). The data generally support, in topographically low regions inland and near the coast, an active, mixing, hydraulic regime comprising young (some hundreds to thousands of years old) meteoric-derived waters extending to around 800-1000 m depth (i.e. indicating high open fracture frequency and associated increase in permeability). At greater depths ancient brines (hundreds of thousands to millions of years old) begin to dominate which indicate near-stagnant conditions (i.e. reduction in open fracture frequency, permeability and groundwater mixing).

A description of the large-scale hydraulic characteristics of the crystalline basement of Sweden can of necessity only be qualitative or at best semi-quantitative. Large-scale flow behaviour cannot be directly measured, however, we expect regionally connected flow paths. Lineaments interpreted from relief maps may be traced as far as hundreds of kilometres. Furthermore, detailed studies of the geological characteristics of major deformation zones have been made by combined use of geophysical data and field mapping. However, it is difficult to demonstrate the lateral movement of deep groundwaters along flow paths of regional scale. Intuitively they must exist, recharging in the mountainous areas inland and discharging along the Baltic coast to the east (and perhaps with deeper systems extending further eastwards beneath the Baltic seafloor), but data are very scarce and in any case most measurements are impossible to interpret because of the immense time scales involved. Long time scales imply a very ancient evolved groundwater chemistry, which restricts the number of hydrogeochemical tools that can be employed to interpret age and residence times. At best ^{36}Cl and $^{3,4}He$ isotopic systematics, for example, can only differentiate between millions and many millions of years, which is inadequate to quantify any kind of groundwater flow velocity and direction, or even degrees of mixing. The chemical and isotopic difference between stagnant brines deep in the bedrock, and near-stagnant brines moving very slowly within a hydraulic structure, will probably be insignificant.

14.3 GEOLOGICAL IMPLICATIONS

14.3.1 Depth to saltwater boundary

When dealing with saline waters the following terminology is commonly used to define the salinity:

Fresh	<2000 ppm Cl^-
Brackish	2000-10000 ppm Cl^-
Saline	10000-100000 ppm Cl^-
Brine	>100000 ppm Cl^-

In general terms, hydrochemical data (Smellie, 1996) show that highly saline groundwaters or brines are found at around 1000 m depth in topographically subdued regions. Note that many exceptions occur due to local geological conditions; saline groundwater can be found at relatively shallow depths (< 500 m) and conversely at depths greater than 1000 m. At Finnsjön (Smellie and Wikberg, 1991) the saline/fresh groundwater boundary in the Precambrian basement is not defined by hydraulic gradients or by density differences, but explained by a low-angle sub-horizontal fracture zone which ranges in depth from 100-250 m. This forms a structural/hydraulic (and also chemical) boundary to circulatory movement of the bedrock groundwater cells. It, therefore, acts as a horizon where groundwaters of considerably contrasting age and chemistry come into contact and partially mix with one another. In other parts of the site fresh water extends down to at least 550 m (the limit of drilling) where the sub-horizontal zone is absent. It is believed that this "hydraulic cage" phenomenon, bounded by sub-horizontal and vertical/sub-vertical structures, may be more widespread in the Fennoscandian basement than earlier thought. Further support for this is found in Finland where marked increases in salinity at Outokumpu (Lahermo and Lampén, 1987) may correspond to borehole intersections with sub-vertical fracture zones.

Examples of well documented studies of relatively fresh water penetrating to greater than 1000 m are few. In Sweden, both Stripa (Davis and Nordstrom, 1992) and particularly Klipperås (Smellie et al., 1987), show groundwaters of shallow to intermediate origin occurring down to depths of 800-1000 m. At Stripa topography and hydraulic head play an important role; at Klipperås the fracture geometry is also important, facilitating groundwater circulation through the bedrock via both vertical/sub-vertical and sub-horizontal fracture zones.

In the Kola deep borehole, SG-3, groundwaters of surprisingly low chloride content (up to 710 mg/l) and pH ranging from 8.0-8.5 were sampled from a broad water-bearing section (4565-4925 m) of low hydraulic conductivity. In the same borehole saline and highly saline groundwaters have been recorded at 900 m (14 644 mg/l Cl) and 1200 m (31760 mg/l). This illustrates the localised influence on groundwater chemistry by hydraulically active zones to considerable depths. The extent of such influence depends on the fracture geometry. For example, their intersection with near-surface or deeply derived groundwater reservoir sources.

14.3.2 Groundwater circulation patterns

In the event of canister degradation, radioactive substances may escape and reach the biosphere. Two factors related to groundwater flow are of great potential importance (SKB, 1995):

- The groundwater flow at the repository level
- The transport time for solutes from the repository to the biosphere

In principle, the major driving forces of fluid flow in the upper crust are:

- pressure gradients (topography)
- groundwater density variations
- thermal convection.

Other sources, such as tectonic dilation and compression, diagenesis and deep fluid sources are also possible under special circumstances (Bredehoeft, 1990), but are not considered important within the studied depth interval of the Baltic Shield. Kukkonen (1988) discussed driving forces for groundwater circulation in the Baltic Shield on the basis of heat flow measurements in boreholes and argued that thermal convection due to radiogenic heat production contrasts can be a realistic mechanism for the deep regional flow. However, in our conceptual models we consider density contrast in groundwater due to thermal differences to be insignificant as compared to topographic driving forces.

The depth to which fluids can migrate within the crust has been a subject of a substantial number of investigations. Different sources of indirect evidence exist since the fluid migration affects heat flow, the distribution of oxygen and hydrogen isotopes as well as the initiation of failure mechanisms in earthquakes. Geophysical data suggest that the maximum depth extent of free water may be as large as 10 to 20 km.

The water table for unconfined flow systems can be considered as a subdued replica of topography. Topographic divides appear to be groundwater divides as well. Under normal conditions the maximum topographic elevation imposes an upper bound on the hydraulic head, whereas the lowest point provides the lower bound. This means that the total difference in elevation gives a constraint on the hydraulic gradient.

With respect to topography, regions can be divided into recharge and discharge areas (Toth, 1963). Given both local relief and regional slope, local, intermediate and regional flow systems will develop (see Figure 14-2). The extent of the flow system is also strongly influenced by the presence of lakes, which can act as discharge, re-charge or through-flow lakes. Groundwater conditions beneath major lakes need to be investigated.

Since there exist very little information on the large-scale hydraulic characteristics of the crystalline bedrock, numerical modelling is an important aid to understand the flow behaviour. Such modelling exercises (e.g., Boulton et al. (1995); Svensson (1996); Voss and Andersson (1993)) show that the depth distribution of effective hydraulic conductivity strongly controls the regional flow field. For a model with a decreasing conductivity with depth, a significant near-surface concentration of flow is obtained.

This effect was also highlighted in analytical solutions for topographically driven groundwater flow (Rehbinder and Isaksson, 1996).

Voss and Andersson (1993) presented a numerical study of a variable-density, regional groundwater flow in the Baltic Shield during post-glacial land rise and coastal regression. They concluded that driving forces due to variable density were much less than the topographic forces at all spatial scales. If present, conductive fracture zones at depth and their connectivity are a major control on the regional flow field. Significant flow may be expected also at great depths under these circumstances.

The most common models for calculating groundwater flow in fractured crystalline rock are based on Darcy's law, which has been shown to be applicable within a wide range of hydraulic gradients. Based on Darcy's law, the groundwater flow at the repository level as forced by regional hydraulic gradients can be estimated. Since the flow rate is directly proportional to the hydraulic conductivity, a three-orders-of-magnitude decrease in bulk permeability over the depth range 1000-5000 m as indicated by the hydrogeological data, yields a corresponding reduction in flow rate by three orders of magnitude for a constant gradient.

The mean velocity of the groundwater is often estimated as the Darcy velocity divided by the flow porosity. Path lengths of groundwater flow from the repository depth to a point of exit at the surface can theoretically vary from the actual vertical depth up to hundreds of kilometres. The transport time of solutes to the biosphere through advection with the groundwater depends strongly on the transmissivity and connectivity of the most conductive structures in the bedrock and is consequently difficult to estimate on the scales treated in this study. However, the great depths and expected lower bulk permeability at depth are favourable as regards to the transport times.

14.3.3 Temperature

Although the lateral temperature gradient is believed not to be important when considering natural groundwater circulation patterns, the vertical temperature gradient is important when considering a deep repository since bentonite becomes unstable at high temperatures. In previous studies (Juhlin and Sandstedt, 1989), a temperature gradient of about 16 °C/km was used in dimensioning the amount of waste that could be stored per hole in the VDH concept. With this temperature gradient it was found that the VDH concept was economically feasible. The vertical temperature gradient in Sweden is expected to vary considerably, but in most areas it will be at or below 16 °C/km.

14.4 EVOLUTION IN TIME

Integration of the multi-disciplinary evidence presented and discussed above largely supports the conceptual models presented in Figures 14-1 and 14-2. Hydraulic gradients of varying intensity have influenced the distribution of the groundwater types and the deep brine interface. This can be illustrated by simply assuming a static groundwater system and calculating the position of the highly saline or brine boundary along the profile represented by Figure 14-2. Based on these calculations, the static model boundary for the brines at Siljan, for example, should be located at shallower levels than observed. This provides some qualitative evidence that the brine boundary at

Siljan has been forced to deeper levels by strong hydraulic gradients driven by topography.

The present data suggest that changes over both short (e.g. thousands of years with respect to glacial events) and long time scales (e.g. millions of years with respect to large scale uplift and erosion) will influence the hydraulic system extending down to the stagnant or near-stagnant brine boundaries. These brine masses appear to be quite stable and may, at most, undergo some vertical movement. Over geological time scales of uplift, erosion and sedimentation, any chemical changes which may occur in the brines will be so slow that near-equilibrium conditions will probably persist. Hydrogeologically, the brine boundary may rise or fall depending on the surface influence. Diffusion effects are expected to be minor since the circulation time scale of the meteoric water is much less than the diffusion time scale is expected to be. Vertical movement of the brine mass is known to have occurred during glaciation events, with the boundary rising during ice cover, and subsequently falling during ice melt. This phenomenon has been interpreted on a small scale (some metres) from fracture mineral studies from the Sellafield Study Site, UK (A. E. Milodowski, per. comm., 1996) and similar on-going studies are now being carried out at Äspö and Laxemar in Sweden and at Outokompo in Finland. Movement of the brine mass, or brine mass turnover, can be dated in some instances using ^{36}Cl since some groundwater mixing will occur, thus, resetting the isotopic signature. Such changes will tend to be restricted to the upper brine horizons.

Apart from the vertical movements, evidence of lateral, regional groundwater flow and hydrochemical evolution are very difficult to measure and interpret. At depths greater than 1000 m the number of reliable sampling locations are very few and the high salt content renders certain measurements unreliable (e.g. pH and Eh). Regional groundwater flow undoubtedly occurs, but the rates of movement are extremely slow and tracing any kind of hydrochemical evolution is a very difficult task. This is reflected in the continuing debate as to the origin of these deep-seated brines.

The climate of Sweden has changed dramatically in the recent past, with ice sheets and permafrost having extended over much of the country as little as c. 10000 years ago. Over longer time scales we know that different processes associated with several glaciation cycles have affected the geological conditions. We expect, in principal, the driving forces which produced past change to continue to vary in the future as they have in the past (Boulton et al., 1996).

The changes in surface conditions at a location induced during build-up and decay of a continent-scale ice sheet can be reasonably well predicted on the basis of our knowledge of present glaciers and numerical ice sheet modelling. However, the conditions at great depth are much more difficult to predict due to complex coupling between different processes.

The changes occurring during a major glaciation phase include e.g., transient effects on the depth to the brine boundary as discussed above, effects on the flow paths of groundwater through the presence of deep permafrost and loading from the ice cap, and melt water flow from the bottom of the ice forced by large hydraulic gradients.

The major mechanical impact on the crust from a growing ice sheet is the isostatic depression due to the large load. During the advance of the glacier the loading also induces an increase in the in-situ rock stresses. This means that the bedrock on a large scale will experience a general compression leading to an increased mechanical stability and a reduction in the number of earthquakes (Johnston, 1987). However, local stress changes and the response of individual fractures are difficult to predict in detail.

During glacial retreat and unloading, existing faults and fracture zones may be reactivated with accompanying seismicity. The deglaciation rebound of the crust following the Weichsel glaciation is still ongoing. These same faults may also be reactivated during loading, however, direct evidence for this is scarce.

It has been established that major climate change, especially glaciations, has a significant impact on the rock mass. Most changes occur, however, closer to the surface than the depth range (1000-5000 m) studied in this project.

15 DISCUSSION OF MODEL

15.1 MAIN FEATURES OF THE MODEL

Main features of the model are:

1. Highly saline water is present at depth in the crust throughout the Baltic Shield.

2. The upper 1-1.5 km in Baltic Shield contains significantly more open fluid filled fractures than the rock below.

3. This upper zone has significantly higher permeability than the rock below. At deeper levels the groundwater flow is generally confined to major fracture zones.

4. Meteoric water circulates within the this upper zone in areas of low topography.

5. Where topography influences pressure gradients meteoric water will penetrate to greater depths, possibly as deep as 10 km in the mountainous areas of north-western Sweden.

6. Rock stresses increase with depth with the minimum stress being horizontal below 1000 m. The difference between the maximum and minimum horizontal stresses increases from 1000 m to 5000 m and is on the order of 50 MPa at 5 km.

7. The temperature gradient is relatively low throughout the Baltic Shield averaging about 15°/km.

8. Lithology can be well predicted as a function of depth in granitic terrains, but in metamorphic volcano-sedimentary terrains lithology is difficult to predict at depth.

9. Major large scale steeply dipping to sub-vertical fault zones (presumably with higher hydraulic conductivity) can be identified by surface geological methods. Major sub-horizontal zones are difficult to map by geological mapping.

15.2 ACCURACY OF DATA AND INTERPRETATIONS

15.2.1 Anisotropy

Anisotropy of the rock may greatly affect our measurements. If fractures have a preferred direction of alignment this will affect both hydraulic conductivity and geophysical measurements. If the minerals making up the rock have a preferred alignment this will affect geophysical measurements, but not hydraulic measurements directly. It may affect them indirectly since fractures may have a tendency to form parallel to the fabric of the rock. Anisotropy is likely to be a more complicating factor in metamorphic terrains where the rocks have been highly deformed. In granitic environments the fractures can be expected to result in a rock mass having more isotropic properties. Analyses of VSP data acquired in the granitic rocks in the Gravberg-1 borehole (Juhlin, 1990) showed the shear wave anisotropy to be only on the order of a few percent. This anisotropy was attributed to the anisotropic stress field preferentially closing fractures aligned parallel to the direction of minimum stress.

Seismic and hydraulic measurements carried out in granitic environments should fairly well measure the isotropic properties of the rock. Measurements carried out in metamorphic environments may only be measuring the rock property in a single direction.

15.2.2 Heterogeneity

Heterogeneity implies that a certain volume of rock consists of different rock types which have different properties or a single rock type whose properties vary considerably. The length scale over which properties change and the degree of change determines the heterogeneity of the rock. Heterogeneity becomes important if rock properties change rapidly over short intervals and if these changes are large. If this is the case, then measurements carried out over one volume may not be relevant to a nearby volume and it becomes difficult to extrapolate and interpolate data. This is obviously a problem in metamorphic areas, but may also be a problem in granitic areas. Granitoid intrusions containing different facies with varying quartz content is an example of this.

In general, however, heterogeneity will be less of a problem in granitic environments than in metamorphic volcano-sedimentary ones (i.e. supracrustal).

15.2.3 3D effects

This is a problem within the field of geophysics. Many of the measurements carried out assume the Earth is 2D. If the Earth is 3D, as it often is, interpretation of the data using 2D methods can be completely wrong. As an example, assume there is a highly conducting sub-vertical fracture zone 1 km away from and parallel to a line where resistivity sounding is being carried out. The sounding experiment will detect this highly conducting zone, but under a 2D, or even 1D in this case, assumption the zone will be interpreted to be sub-horizontal at a depth of 1 km. Again, this is a problem which is probably more severe in metamorphic areas than in granitic areas. However, seismic reflection studies on the island of Ävrö show that the 3D orientation of fracture zones need to be taken into account when interpreting reflection seismic data from this granitic area (Juhlin and Palm, 1997)

3D effects are also necessary to consider in the description of hydrogeological properties and the regional groundwater flow pattern. Topographic relief as a major driving force of flow is not 2D as indicated in Figure 14-2 and, moreover, over dimensions of kilometres to hundreds of kilometres, fluid movement is significantly influenced by large-scale features, such as fault zones, that can be expected to cross the dominating flow direction.

15.3 REGIONAL DIFFERENCES WITHIN THE BALTIC SHIELD

Given that the Baltic Shield is composed of rocks of differing ages, composition, tectonic history and glacial history one may expect significant variations of conditions at depth within the shield. However, the main features of the model outlined in chapter 14 should generally be valid throughout the shield. The important point is that in crystalline rock the primary porosity is very small compared to for instance sandstones, therefore, only minor differences in the matrix porosity due to lithology exist. This results in the fluid flow being governed primarily by the fracture porosity which is controlled by the brittle tectonic history rather than by the lithology.

In order to study the proposed upper fractured interval quantitatively it is necessary to investigate the rock below 1 km and compare it directly to the rock above this depth. Only in the Siljan Ring area and Laxemar have boreholes been drilled to these depths in Sweden. Results from the Siljan boreholes appear to be consistent with the proposed model. At Laxemar, the observed fracture (open plus sealed) frequency is relatively constant with depth. However, the number of open fractures and the degree to which they are open may be much higher in the upper km.

15.4 COMPARISON WITH OTHER AREAS

The present study is not comprehensive enough to compare conditions at depth with other areas. However, we can note that the Canadian Shield has similarities to the Baltic Shield when refraction and hydrogeochemical data are considered. The refraction data show rapidly increasing velocities in the upper 1-2 km implying less open fractures below these depths and the hydrogeochemistry shows large increases in salinity below 1 km. Note that in sonic log data from mining areas in Canada that there is not a clear pattern of decreasing fracturing with depth. Even the Arabian Shield shows a marked increase in seismic velocity in the upper km which is observed in the Baltic Shield. The KTB boreholes show that surface waters circulate to about 500 m depth (Kohl and Rybach, 1996) and that this upper 500 m is more fractured than the rock below (Pechnig et al., 1997). Increased fracturing is also apparent in the upper c. 1 km in the NAGRA Böttstein borehole in Switzerland and may be present in the RH12 borehole in Cornwall.

15.5 HOW TO IMPROVE AND TEST THE MODEL

Short of drilling boreholes to 3-5 km depth, there are a number of ways in which the proposed model can be improved and tested. These include:

1. Salt water profiling

2. Refraction and reflection seismics

3. Isotope studies of fracture minerals from deep boreholes

4. Detailed fracture mapping

5. Earthquake analyses

6. Numerical modelling of large scale fluid flow.

Recent results using surface electrical methods in the Laxemar area show the depth to more conductive rock (higher salinity in the pore space) can be relatively well determined (Carl-Axel Triumf, pers. comm., 1997). These methods can be applied throughout Sweden where the salinity increases sharply at depths of less than 3 km, thus allowing the depth to saline pore water to be mapped. Controlled source seismic methods may be used to map the velocity function in detail in the upper crust and image sub-horizontal fracture zones. In existing boreholes, isotope studies of fracture filling minerals may provide constraints on groundwater circulation patterns. Detailed fracture mapping as carried out by Barton et al. (1994) can provide more information on the ratio of open to sealed fractures as a function of depth. A dense seismic network to monitor events in the upper crust could constrain changes in stress direction and magnitude over a large volume. Coupled with geodetic and controlled source seismic data, identification of active fracture or fault zones may be possible through such a network. Numerical modelling is probably the only method that can be used to constrain the deep long term groundwater circulation patterns on a regional scale.

16 CONCLUSIONS/RECOMMENDATIONS

Review of the literature allows us to make the following observations from surface studies and borehole data:

Construction aspects of the VDH concept
The construction and drilling aspects described in Juhlin and Sandstedt (1989) are still valid today. Improvements in drilling technology have been made, primarily in directional control of the borehole, which should make the VDH concept safer and more economical than in 1989.

Geophysics
The seismic velocity increases rapidly in the upper c. 1 km in the Baltic Shield. This increase appears to be present everywhere irrespective of lithology, but is perhaps most apparent in granitic terrains. The lower velocities in the upper km are attributed to open water filled fractures. Analyses of borehole geophysical data confirm higher levels of open fractures in the upper km not only in the Baltic Shield, but also in other crystalline rock areas. Measurement and extrapolation of borehole data give a temperature gradient in the Baltic Shield in of about 15° C/km. This temperature gradient is predicted in the uppermost crust from lithospheric modeling of heat flow in the Baltic Shield.

Hydrogeology
Although data are sparse, permeability data also indicate less open fracturing below 1 km. In the available data, the permeability is about 3 orders of magnitude lower at 5000 m than at 1000 m. In general, the pore pressure is close to hydrostatic in all boreholes reviewed. The one exception is the Kola borehole in the Baltic Shield of Russia where pore pressures of 40-50 % greater than hydrostatic have been reported in the depth interval 1000-2800 m.

Hydrochemistry
In general, pore waters are relatively fresh down to at least 500 m throughout Sweden, but become more saline below this depth. At great depth, brines are present. The depth to these brines appears to be dependent upon geographical location and hydrostructural controls. High gas content may be observed in brines in Sweden and Canada. Investigations show that bacteria exists and flourishes at great depth, independent of the biosphere, and may contribute to the large quantities of methane observed.

Mechanical properties and the state of stress
Mechanical properties of the rock are defined in terms of strength and deformability and studies carried out near the surface are relevant for quantifying these properties at depth. Near the surface, the parameters are dependent on the volume of the rock mass under investigation. The stress appears to increase linearly with depth down to 5 km, although quantitative measurements below 1 km are lacking. The vertical stress is generally the intermediate stress implying the tectonic regime is strike-slip faulting.

Geology
Prediction of lithology at depth based on surface geological information is difficult in volcano-sedimentary rocks due to the heterogeneous nature of these rocks. In granitic environments it is easier to predict the lithology in the upper 5 km. Fracture mineralogy is indicative of how an observed fracture evolved and the palaeo-fluid history. If the minerals are in equilibrium with the surrounding rock then the fracture probably developed under ductile conditions, otherwise it developed under brittle conditions. Brittle fractures are probably the ones which are most likely to be highly permeable. Not all boreholes show decreased fracturing with depth, in apparent contradiction with the geophysical and hydrogeological data. This contradiction is reconciled by noting that most geological core logs only show where fractures are present, not whether they are open or not. If open fractures were logged it is likely that their frequency would decrease with depth in accordance with geophysical and hydrogeological data. Prominent large scale sub-horizontal fracture zones, which may be highly difficult to predict from surface geological data, are identified at several localities in the Baltic Shield. These conductive zones have to be considered in studies of the fluid flow patterns.

Based on the above observations we have developed a model for the upper 5 km of crust for the Baltic Shield. The upper 1 km of the crust consists of more fractured rock, or at least rock with more open fractures, compared to that below. In areas of low topography, this upper fractured interval limits the depth of meteoric water circulation and highly saline waters may be expected below 1 km. Closer to mountainous areas the topography greatly influences meteoric water circulation patterns with these waters penetrating down to depths on the order of 10 km. The temperature field variations within the shield are small enough that they are not expected to have significant effect on the water circulation patterns. Earthquake activity is low in the shield area, in general, with higher concentrations along the west coast of Norway, the north-eastern coast of Sweden and south-western Sweden. Even in these areas the earthquake activity is low compared to active south-eastern Europe. The largest earthquakes occur deep in the crust due to increasing differential stress with depth. Earthquakes may be concentrated towards large zones of weakness where water circulation may be expected to be enhanced.

Future work
The following recommendations for future work can be made:

1. Continue monitoring results from deep drilling programmes.

2. Continue monitoring results from seismic and electrical geophysical studies on the Baltic Shield.

3. Develop models for large scale hydrogeological description of the Baltic Shield and carry out sensitivity studies.

4. The following geoscientific methods may be used to study relevant parameters as a function of depth

- Geoelectric methods for mapping the depth to saline water in the Baltic Shield
- Refraction seismics for mapping the upper more fractured part of the crust

- Reflection seismics for mapping discrete sub-horizontal fracture zones or lithological contacts
- Earthquake studies using a local dense network of stations
- Isotope studies on fracture minerals from cuttings in the Gravberg-1 borehole to determine hydrochemical flow patterns
- Detailed hydraulic measurements in the KLX02 borehole
- Detailed hydraulic measurements in the KTB borehole
- Integrated analysis of detailed geoscientific data from a deep borehole
- Studies of open versus sealed fractures from SKB study sites.

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