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Gabbro as a host rock for a nuclear waste repository

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ABSTRACT

As an alternative to granitic rocks, gabbro and other basic rock types have been investigated with respect to their suitability to host a nuclear waste repository. The present report summarizes and examines existing geoscientific knowledge of relevance in assessing the potential merits of gabbro as a repository host rock. Implications in terms of site selection, repository construction and post-closure repository performance are also discussed. The objective of the study is to provide a basis for decisions as regards future consideration of the gabbro alternative. It is found that there are rather few gabbro bodies in Sweden, that are potentially of sufficient size to host a repository. Thus, gabbro offers little latitude as regards site selection. In comparison to siting a repository in granitic rocks, this is a major disadvantage, and it may in fact remove gabbro from further consideration. The potential advantages of gabbro refer to repository performance, and include low hydraulic conductivity and a chemical environment promoting efficient radionuclide retardation. However, results from field investigations show that groundwater flow in gabbro bodies is largely controlled by intersecting heterogeneities, in particular granitic dykes, that are significantly more conductive to water than the gabbro. In the far-field scale significant to repository performance, this may reduce or eliminate the potential effects of favorable hydraulic and chemical characteristics of the gabbro itself. In conclusion, there are apparent difficulties associated with siting a repository in gabbro, due to lack of sufficiently large gabbro bodies. On the basis of the present state of knowledge, no decisive differences can be demonstrated when comparing gabbro with granitic rocks, neither with respect to repository construction, nor as regards repository performance.

CONTENTS

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1 BACKGROUND

The Swedish nuclear waste management program has focused on granite and gneiss as the major candidate host media for a repository for spent nuclear fuel. Mafic rock types, in particular gabbro, has been suggested as alternatives, and the potential suitability of gabbro with respect to nuclear waste disposal has been studied and discussed at several occasions over the past twelve years.

The present report summarizes and examines existing geoscientific knowledge of relevance in assessing the potential merits of gabbro as a repository host rock. Implications in terms of site selection, repository construction and post-closure repository performance are also discussed.

In the first part of the report, an overview is given of the sources of data available for the present study. A description of the scope of research and main results of previous investigations relating to gabbro, and conducted within the Swedish radwaste program, is also included.

The main part of the report, comprising chapters 4 through 7, compiles existing knowledge on the geological, geohydrological, geochemical and geomechanical properties of gabbro. This part is based mainly on three recently completed supporting studies, more narrow in scope than the present work, but penetrating deeper into the data available and matters of concern within the different geoscientific disciplines. The presentation also draws upon a study conducted by SKB in cooperation with TVO - the organization managing the finnish radwaste program.

Reports from these background studies are available as follows:

1 Geomechanical and rock engineering characteristics of gabbro (Leijon, 1992). (compiles fundamental thermal and mechanical properties of gabbro, and presents available data on rock stress conditions as well as practical experience from underground construction in gabbro rocks).

2 Gabbro: Geological and hydrogeochemical features (Smellie, 1992). (a review of available data regarding the geological, mineralogical and hydrochemical characteristics of gabbro, in Sweden, Finland and Canada).

3 The hydraulic properties of different greenstone areas (Liedholm, 1992). (an extensive statistical analysis of data available from well tests. Aimed specifically at evaluating possible differences in hydraulic properties between greenstones and other crystalline rock types).

4 Gabbro as a host rock for a repository. Swedish experiences (Ahlbom, 1992). (an overview of gabbro investigations in the Swedish radwaste program. Distribution and shape of gabbro bodies and implications on site selection are discussed, as are the pros and cons of gabbro as a repository host rock in general terms. This study was made in collaboration with TVO).

Chapters 8 and 9, finally, provides a general discussion of gabbro as a repository host rock, and the overall conclusions resulting from the present study.

The objective of the present study has been to provide a basis for decisions as regards future consideration of the gabbro alternative. Such decisions must largely rely upon comparative evaluation procedures. Therefore, a comparative mode of presentation has been chosen throughout the report. Thus, the data presented and processes discussed with reference to gabbro are, to the extent possible, put in relation to the corresponding characteristics of granitic rocks.

2 GABBRO - GENERAL DESCRIPTION

2.1 Petrology

Gabbros are the normal products of the middle stages of fractionation of a basaltic magma. As a result they are typical of layered intrusions, but are also encountered in thick differentiated sills and smaller intrusions. Classic examples of layered intrusions include the Skaergaard Intrusion on Greenland, the Stillwater Intrusion in Montana, USA and the vast Bushveld Complex in Transvaal, South Africa.

Gabbro is generally a dark colored and rather heavy rock type. Grain sizes varies from a few mm up to a few cm. Dark colored ferrous or magnesium minerals, of which the most common is clinopyroxen ($Ca(Mg,Fe,Al,Ti)Si_2O_8$), constitutes 20-60 % of the rock type. Other common dark minerals are olivine, hornblende, biotite and chlorite. The most important light minerals are plagioclase, a feldspar with a composition between albite ($NaAlSi_3O_8$), and anorthite ($CaAl_2Si_2O_8$). Quartz may be present, although seldom more than 5 %. Common accessory minerals are magnetite (Fe_3O_4) and ilmenite ($FeTiO_3$).

In a strict sense gabbro is defined as (Streckeisen, 1976): <90 % dark mineral (by volume), <10 % alkali feldspar and <5 % quartz (of the total amount of feldspar plus quartz). The anorthitic content of the plagioclase should be 50 % or more. In reality, these mineral limits are often exceeded by the natural variation of the gabbro. Transitions to other mafic rock types are common. For example transitions are often found to diorite (anorthite content less than 50 %), to norite (more orthopyroxene than clinopyroxene), to tonalite (quartz content exceeds 20 % of the feldspathic minerals), and to ultramafic rock types (e.g. pyroxenite, hornblendite, peridotite) when the dark colored minerals exceeds 90 % of the total composition. Along the, so called, Protogin zone in southern Sweden sheetlike bodies of norite are common. These are termed hyperites.

When not specifically stated the term "gabbro" in this report is used as synonymous for several basic rock types, including diorite, dolerite, norite and hyperite. The terms "basite" or "greenstone" are used when no distinction is made between plutonic or volcanic basic rocks.

2.2 Physical properties

Typical values of selected, fundamental physical properties of gabbro rocks are summarized in Table 1, together with indications of ranges of variation. Corresponding values for granitic rocks are also indicated. Some of the mechanical properties are further discussed in Chapter 7.

The thermal and thermomechanical properties, in particular thermal conductivity and thermal expansion behavior, are of special interest with respect to repository

Table 1. Typical values of basic physical properties for gabbro and for granitic rocks.

Property	Typical value			
	Gabbro	Granite	Consistent difference gabbro vs granite	Variation
Thermal conductivity(W/mK)	2.8	3.5	Yes	Moderate
Thermal capacity ($Jkg^{-1}K^{-1}$)	750	750	No	Small
Thermal diffusivity($m^2s^{-1}10^{-6}$)	1.25	1.75	No	Moderate
Coeff. of thermal exp. (10^{-6})	6	8	?	Large
Mass density (kg/m^3)	3000	2650	Yes	Small
Young's Modulus (GPa)	80	50	No	Moderate
Compressive strength (MPa)	280	180	No	Large

performance, since they have implications on heat transfer and thermomechanical load generation in the post-emplacement phase. The thermal conductivity of crystalline rocks is largely controlled by their modal composition. The conductivity of quartz (about 7.7 W/mK) is 2-4 times higher than for most other minerals, and the quartz content of a rock material therefore has a large effect on its conductivity. This explains why mafic rock types such as gabbro invariably show lower conductivity than granite and other acidic rock types. Figure 1 shows a comparison of conductivity values for selected rock types including gabbro, derived from a comprehensive investigation of thermal properties of Swedish rocks presented by Sundberg (1988). The data refer to temperatures less than 100 °C. As a rule of thumb, the conductivity of crystalline rocks decreases with 1 ‰ per °C temperature increase, mafic rock types being no exceptions. For gabbro, this corresponds to about 0.2 W/mK per 100 °C temperature increase.

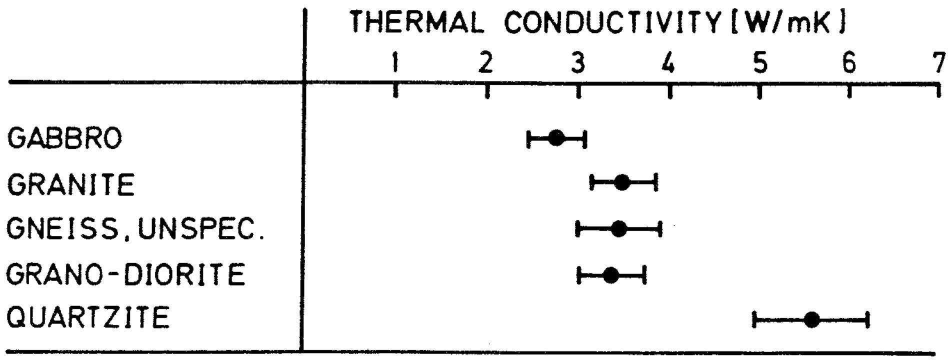

Figure 1. Thermal conductivity values for selected rock types, mean values and standard deviations.

Data on thermal capacity and thermal diffusivity of gabbro rocks are scarce in the literature. They can, however, to good approximation be substituted with results for basalt and diabase, due to the similarities in mineralogical composition. The thermal capacity (or specific heat) of rocks varies within a rather narrow interval. A theoretical calculation for gabbro, based on modal composition, yields the value given in Table 1. Experimental results are in agreement with this, and also show that a range of variation (expressed as standard deviation) of about 15% may be assumed for this parameter. The thermal diffusivity of mafic rocks are generally lower than for granite/gneiss, but data available are scattered.

The linear coefficient of thermal expansion defines the relative change in length of the unconfined material, per unit temperature change. The parameter is dependent on temperature and pressure, but the nature of these relationships can vary significantly between different rocks. Figure 2 shows linear coefficient of thermal expansion, plotted as a function of temperature, for gabbro and for granitic rocks. Data are taken from various sources in the literature.

It can be seen that the thermal expansion coefficient falls briefly within the range $4 \cdot 10^{-6}$ to $10 \cdot 10^{-6}$ for temperatures less than about 150 °C. Closer examination of the data yields average values as presented in Table 1. The coefficient of thermal expansion increases with temperature, Figure 2, but data available for gabbro are insufficient to determine any specific relationship.

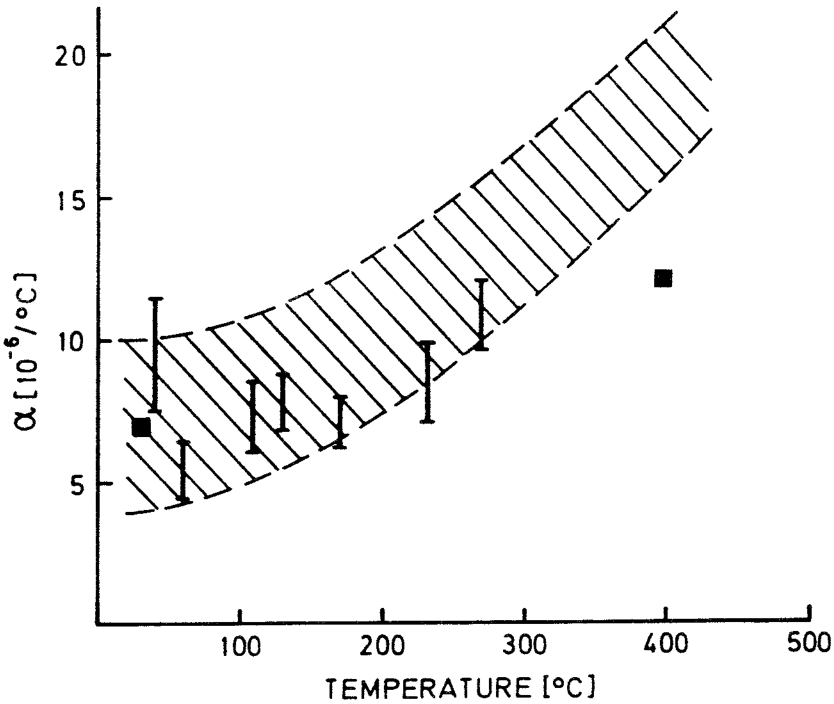

Figure 2. Linear coefficient of thermal expansion for gabbro (points and bars) and for granitic rocks (shaded area).

3 AVAILABLE FIELD DATA

3.1 General

Basic rock types, including gabbro, have been of considerable interest for ore prospecting activities. Many basic rock bodies have been drilled and core samples have been analyzed. However, very little of this wealth of data can be utilized to assess repository performance. This is because in most cases these studies do not concern with fracture zones and fractures, fracture mineralogy, groundwater chemistry or hydraulic properties. Another obstacle is that prospecting data are, with a few exceptions, never published.

Therefore, most of the data presented in this report originate either from studies aimed specifically at assessment of parameters linked to repository siting and performance, or from projects in mining and civil engineering. Data on more fundamental parameters have also been collected from the general literature. Furthermore, well statistics has been an important source of information in assessing the geohydrological characteristics of mafic rock types. The systematic collection of well capacity data conducted by the Swedish Geological Survey has resulted in a database presently containing some 100000 wells, distributed all over the country. This allows the geohydrological conditions in different geological regimes to be evaluated and compared on a statistical basis. The major drawback of this information is that it refers to the uppermost 10-100 m of the bedrock.

Within national radwaste site investigations, gabbro has been the main rock type at two sites, Taavinunnanen in northern Sweden and East Bull Lake in Canada. Data from these sites are frequently referred throughout this report. As far as know, Sweden, Finland and Canada are the only countries in which gabbro has been specifically studied as part of radwaste management programs. The activities within the Swedish program are outlined in the section following. Furthermore, a comprehensive overview of the Taavinunnanen studies is appended to this report.

Within the Finnish radwaste program, studies for investigating and evaluating gabbro are currently in progress (TVO, 1991). No data has however been published so far. Valuable data concerning groundwater chemical conditions in gabbro have also been produced as part of a program for characterizing the geochemistry of deep groundwaters (Blomqvist et al., 1986; Nurmi et al., 1988; Halonen et al., 1990).

Finland has also been a major source of data concerning the rock mechanical and engineering characteristics of gabbro. This is because Finland hosts several mines in mafic formations, and because a large gabbro intrusion at Mäntsälä has been investigated to large depths, as part of a storage program for natural gas.

In Canada, the East Bull Lake Pluton, a layered gabbro-anorthosite intrusion located some 90 km west of Sudbury in Ontario, has been extensively studied by

Atomic Energy of Canada Limited (Raven et al., 1985; 1987; Kamineni et al., 1985; Kamineni, 1986, 1987; Brown and Kamineni, 1987; McCrank et al., 1984, 1988; McNutt et al., 1987; Bottomley et al., 1990). Field investigations at East Bull Lake included comprehensive drilling and borehole testing. The pluton was found to consist of a number of lithological units, including several types of gabbro, anorthosite and troctolite. Fracture frequencies recorded were generally considerably higher than those encountered in the gabbro bodies investigated in Sweden and Finland.

3.2 Inventory studies within the Swedish radwaste program

Initial studies concerning gabbro were initiated in 1979 and has since then intermittently been a part of the Swedish programme. The main part has been to locate all major gabbro bodies in Sweden and to obtain data regarding geological, hydrological and hydrochemical characteristics of gabbro. However, in spite of the comprehensive inventory studies, only one deep borehole has been drilled (the Taavinunnanen borehole). Two other sites were selected for drilling, but at both sites, drilling was terminated before the borehole reached its target depth.

This section presents an overview of the "history of gabbro" in the Swedish spent fuel disposal programme from 1979 until today. The main activities and the main results are briefly described in Table 3.

The site selection and site characterization programme was during 1979-1982 managed by the governmental organization National Council for Radioactive Waste (PRAV). The management was during 1982 transferred from PRAV to the Swedish Nuclear Fuel and Waste Management Co. (SKB). Both organizations contracted the Geological Survey of Sweden (SGU) for the main part of the site selection and site characterization studies. During 1982 these studies were transferred to the Swedish Geological Co (SGAB).

Large gabbro massif in northern Sweden

Gabbro was included in the site selection studies as early as 1979-80. This was based on suggestions from some of the KBS 1- and 2 reviewers, but also from several geologists within the Geological Survey of Sweden (SGU). The main reason for the SGU geologists to suggest gabbro was the low water capacities normally found in wells drilled in basic rock types. Another reason was that gabbros often appear as competent rock bodies compared to their surroundings. This was observed both in airborne magnetic maps and by direct observation in the field.

Table 3. Activities and main results for Swedish gabbro studies.

Period	Activity	Main results
1979-80	Reconnaissance for gabbro in northern Sweden	Selection by PRAV of four large gabbro massifs for field studies.
1980-81	Field studies of four gabbro massifs	Selection by PRAV of the Taavinunnanen gabbro for drilling.
1980-81	Reconnaissance for gabbro in central Sweden	Selection of a site with a several hundred m thick dolerite sheet overlaying gneiss. The site was later abandoned due to complicated landownership.
1981-83	Drilling of the Taavinunnanen borehole and subsequent borehole measurements	Unfavorable results mainly due to frequent occurrence of conductive granite dykes and other heterogeneities. Future reconnaissance should focus on homogenous gabbro massifs with high accessibility.
1982	Reconnaissance for ultramafic rock types in the Swedish mountains	Identified rock bodies too small for a repository. Further studies canceled.
1982-83	Reconnaissance for large accessible gabbro massif in northern Sweden	Two sites were regarded favourable, of which the Gallejaure formation was selected. Geophysical modelling indicates gabbro at 300 m depth.
1983	Drilling of the Gallejaure borehole	Since no gabbro was found at 600 m depth the drilling was canceled and the site closed.
1983	Continued reconnaissance for large accessible gabbro massifs in northern Sweden	Three gabbro bodies recommended for further studies (out of 99 gabbro massifs).
1984-85	Evaluation of gabbro suitability as a host rock for a repository	"difficult to find suitable gabbro massifs. Favourable conditions might exist for homogenous gabbro. More data are needed".
1983-85	Nationwide reconnaissance for identification of all gabbro massifs >1 km^2	453 gabbro massif identified. A later study showed that only 342 fulfill the size requirement. For assessing the general suitability of a homogenous gabbro the Kolsjön gabbro, outside Uppsala, was selected for drilling.
1985	Drilling of the Kolsjön borehole	The drilling was stopped after 10 m depth due to local protests. Further work on the site was canceled.
1986	SKB R&D-programme 86	SKB concludes - difficult to find sufficient large and homogenous formations of gabbro - no further studies of gabbro.
1987	Complementary reconnaissance for gabbro by SGU	SGU disagrees with the R&D programme 86. A complementary study by SGU identifies 72 "additional" gabbros. However, a control shows than most gabbros are too small or have earlier been studied by SKB.
1990-92	SKN argues for continued studies of gabbro	SKB starts three studies to evaluate if there is any reason for changing its gabbro policy. The studies include chemical and hydraulic characteristics, as well as constructability of gabbro. SKB conclusions will be reported in R&D programme 92.

During 1979-80 a study was therefore conducted by SGU, on contract from PRAV, in which the existing data on large gabbro bodies in the northern part of Sweden (Norrbotten) were compiled, and possible sites for field studies were suggested (Ahlbom et al., 1980; Henkel, 1981). More specifically, the study concerned interpretation of existing data from airborne magnetic and ground gravimetric surveys, and petrophysical measurements of outcrop samples. As a result from the work, four large gabbro massifs were recommended for further investigations.

These gabbro massifs were during 1981 subject to air-photo interpretation for identification of faults and outcrops, and later to reconnaissance studies in the field for obtaining geologic and tectonic characteristics (Ahlbom & Olkiewicz, 1981). The result was a recommendation to select the Taavinunnanen gabbro as a site for a deep borehole.

Thick dolerite sheets in northern Sweden

At the same time, 1981, reconnaissance studies for site selection in the Västernorrland county were in progress. This county is characterized by 250-300 m thick and extensive subhorizontal sheets of layered dolerite occurrences (Ulvö dolerite complex, Larson, 1980). Although these dolerites are generally highly fractured, water capacities in dolerite wells are low. Median well capacity for the Ulvö dolerite is 400 l/h, which can be compared to 750 l/h for sedimentary gneiss and 1000-1800 l/h for different types of granites (Ahlbom & Olkiewicz, 1981).

To take advantage of the low-permeable dolerite it was suggested to select a site where a thick dolerite sheet occurs between a sedimentary gneiss at 500 m depth and the ground surface. The dolerite sheet would in this case act as a barrier against vertical groundwater movements. The sheet could also be used as a marker horizon to identify stable blocks in which no faulting has occurred since the intrusion of the dolerite. In fact, one such site was recommended (Ahlbom & Olkiewicz, 1981). Because of private landownership the site was however never investigated.

Taavinunnanen investigations

The management of the site selection programme was during 1982 transferred from PRAV to SKB. At that time the borehole investigations of the Taavinunnanen gabbro was in progress. The results from the core logging and mineralogical/petrographical studies were therefore reported to PRAV (Ahlbom et al., 1982), while other borehole measurements, including geophysical logging, hydrological tests and groundwater sampling, were reported to SKB (Gentzschein 1983; Smellie, 1983; Albino, 1984; Larson and Tullborg, 1984; Laurent 1984; Gentzschein and Tullborg, 1985).

The surface geological mapping, and the results from the 700 m deep borehole, showed that the Taavinunnanen gabbro massif was strongly heterogenous both with respect to internal gabbro structures and because of a high frequency of granitic dykes. These heterogeneities make the site unfavorable for further studies. It was therefore recommended that forthcoming site selection for gabbro should preferable focus on homogenous gabbro bodies. An overview of the Taavinunnanen studies is appended to this report.

Ultramafic rocks in the Swedish mountains

In reviewing KBS 1- and 2 reports, the University of Gothenburg suggested ultramafic rock bodies in the Swedish mountains as suitable repository host rocks. To investigate this possibility, the Univ. of Gothenburg was during 1982 contracted by SKB to elaborate on the possible advantages with these rock types and to present locations of large ultramafic rock bodies (Stigh, 1982).

There are at least two potential advantages with ultramafic rock bodies. Firstly, they are expected to have a high self-sealing potential due to the transformation of olivine to the "sealing mineral" serpentine, when olivine is in contact with water. Secondly, considering those located in the Swedish mountains, the competent ultramafic bodies are expected to be mechanically stable in the "soft" surrounding bedrock consisting of sedimentary rocks. (This is also shown by the fact that no fault has been observed to penetrate an ultramafic body in this region).

One site, located in the largest of the ultramafic bodies, was suggested for further studies. However, a field reconnaissance revealed that the rock body was still not large enough to host a repository. The difficulties in finding a large enough rock body, in combination with several unfavorable non-geological conditions (alternative use of land, transportation of spent fuel etc.) were the main reasons for SKB not to further investigate the possibility of a repository in ultramafic rocks.

Gallejaure massif

The site selection studies for gabbro continued during 1982-83. The outcome of these studies was the recommendation of two gabbro massifs for further studies. One of them was the Gallejaure massif located on the border between the Norrbotten and Västerbotten counties.

The Gallejaure massif was regarded favorable for several reasons. Firstly, because of prospecting activities there is a large geological, geochemical and geophysical database for the region. Secondly the massif has a large area (100 km^2), and thirdly Gallejaure is, compared to other large gabbro bodies, rather favorably located about 90 km from the coast and close to existing railway. There was one main uncertainty - the gabbro body does not outcrop. Instead the outcrops overlaying the gabbro consist of monzonite. Large magnetic and gravity anomalies indicated however the existence of a 4-5 km thick basic rock body with its upper surface located at 300 m depth.

A reconnaissance borehole was drilled, but since no gabbro had been found when reaching a depth of 600 m, SKB decided to terminate drilling and to close the site. The reason for the discrepancy between the predicted depth to the gabbro and the drilling result has not been evaluated. There is no report describing the drilling activities nor the core logging.

Continued site selection for gabbro in northern Sweden

The reconnaissance work for selecting a large homogeneous gabbro in northern Sweden continued during 1983. A total of 99 gabbro bodies were included in the investigation of which 12 were visited. Three gabbro bodies were recommended for further studies.

Evaluation of "pros and cons" with gabbro

A generic study was made during 1984-1985 to assess the existing knowledge regarding advantages and disadvantages with gabbro as a host rock for a repository for spent fuel (Brotzen, 1985). The general conclusion from the study was that in spite of the data gathered from notably Taavinunnanen in Sweden and East Bull Lake in Canada, there still exist large gaps in the knowledge regarding properties and conditions of gabbro as a repository host rock. For example, there are very few data regarding hydraulic properties at depth, and reliable chemical data from deep groundwater in gabbro are virtually non-existent.

Nationwide inventory study of gabbro massifs

Simultaneously with the generic study, the inventory studies in northern Sweden were extended to include all known basic rock bodies within the entire country. This comprehensive study identified 453 mafic bodies with a size more than 1 km^2. Some of the more promising were briefly studied in the field and four gabbro bodies were investigated more thoroughly with gravimetric profiles to determine their size and in particular their depth.

Kolsjön gabbro

To fill the gaps identified by the generic study it was decided during the autumn of 1985 to drill a deep borehole in the Kolsjön gabbro, close to Uppsala. Although this gabbro is rather small, 4 km^2, it displays more or less all the wanted characteristics, i.e. a depth exceeding 1000 m (from gravity modelling), a flat topography, rather homogenous gabbro, a large degree of outcrops and few intersecting lineaments. Also there is only one landowner, a forest company.

The borehole reached a depth of only 10 m before it was stopped as a consequence of local protest. Shortly after, SKB decided to close the site.

Complementary inventory study by SGU

The problems of finding a large homogenous gabbro body with acceptable location, considering population density, transport possibilities, landownership etc., caused SKB to, in their R&D-programme 86, state "appraising the total knowledge acquired concerning final disposal in rock formations, further studies of gabbro are not considered necessary. One reason for this judgement is that it will probably be difficult to find sufficiently large and homogeneous formations of gabbro, which is a relatively uncommon rock type in Sweden".

In their review of R&D-programme 86, the Swedish Geological Survey (SGU) claimed that there exist sufficiently large gabbro bodies that are suitable for a repository and because of this the gabbro studies should continue. This view was shared by the National Board for Spent Nuclear Fuel (SKN) in their report to the government (SKN, 1987).

As a result SGU was asked by SKB to report all large gabbro bodies in addition to the 453 mafic bodies earlier identified. The SGU report identified an additional 72 bodies. However, a control showed that many of these "new" rock bodies were in fact included in the earlier inventory studies but under different names. Other "new" gabbro bodies were to small to be considered. Some new gabbros were however added. All together, the SGU study did not change the overall picture regarding the occurrence of gabbro in Sweden, and consequently SKB found no reason to change their view on further investigations in gabbro as expressed in the R&D-programme 86.

On-going studies for gabbro

In their report to the government regarding SKB R&D-programme 89 (SKN, 1990), SKN states that several reviewers do not agree with the SKB conclusion to remove gabbro from further studies. SKN therefore concludes that SKB should continue to investigate basic rock types.

SKB responded during 1990 by initiating three studies, dealing respectively with chemical characteristics of gabbro and its' groundwater, hydraulic characteristics of basic rock types as determined from well surveys, and finally geomechanical characteristics and rock engineering experiences. A fourth study was made in collaboration with TVO (Teollisuuden Voima Oy) in which Swedish experiences regarding gabbro investigations are summarized. Reports from these studies have been issued as indicated introductory.

3.3 Gabbro in civil engineering and mining

Experiences from rock engineering efforts in gabbro, involving excavations, are important, because they represent behavior in full scale and because they apply directly to feasibility of constructing a repository in gabbro. Rock engineering characteristics are, however, controlled not only by rock type, but also by site specific structural conditions. In compiling existing data, information must therefore be critically examined to ensure validity with respect to the parameter studied and the present application.

Excavations in gabbro for civil purposes exist but are few, due mainly to the limited occurrence of gabbro in areas where excavations have been needed. Information relating to construction feasibility, stability and water conditions has been obtained from tunnelling efforts in the Gothenburg area and from defense-related facilities (Ludvig, 1991). These excavations are all located at shallow depths.

Practical experiences from excavations in gabbro at depth originate exclusively from mines. This knowledge is invaluable, because it represent conditions of rock stress that are appropriate with respect to repository construction. It should be emphasized though that mines, as opposed to potential sites for nuclear waste disposal, generally are located in geologically and tectonically disturbed areas. Swedish mines located in mafic rocks are few and relatively shallow. More valuable information is available from mines in Finland, notably the Otanmäki and Kotalahti mines (Lindholm, 1991). Experiences regarding rock stresses and stability conditions have been drawn from these mines. In the Sudburry District in Canada, extensive, deep mining is conducted in mafic rock, including gabbro and norite, but structural conditions in these mine are generally different from those of interest here (Swan, 1991).

In 1989, a large gabbro intrusion near Mäntsäla, some 40 km north of Helsinki in Finland, was investigated as part of a site selection program for a potential deep-sited natural gas storage facility (Särkkä, 1990; Tiitola, 1990). The work did not include excavations, but surface- and borehole investigations. Results are of interest for several reasons; Firstly, because the intrusion shows geological characteristics that would be part of the requirements for a rock body considered for hosting a repository. This includes sparse fracturing and large size (lateral dimensions 3 km by 3 km, and depth at least 1000 m). Secondly, two holes were drilled in the gabbro to depths of about 900 m. Investigations in these boreholes included geological and geophysical logging, hydraulic tests and stress measurements. A similar investigation program was also conducted in granitic rocks near the gabbro intrusion.

4 DISTRIBUTION AND SHAPE OF SWEDISH GABBRO BODIES

4.1 Database of basic rock bodies

As described in the previous chapter, inventory studies for gabbro have been a part of the Swedish programme for many years. All identified basic rock bodies larger or equal to 1 km^2 have been stored in a database. Presently, this database probably includes more or less all larger gabbro bodies (>20 km^2), and probable also 90-95 % of the smaller bodies greater than 3-4 km^2. The completeness of the database enables analyses regarding the spatial- and size distributions of basic rock bodies in Sweden. As mentioned in Chapter 3 the completeness of the database was tested by an independent study made by the Geological Survey of Sweden (SGU) in 1987.

The database includes the locations and aerial extent of in total 342 basic rock bodies (including gabbro bodies reported by SGU in 1987). For each of these, there is information regarding geographical, geometrical and geological conditions. References to relevant geoscientific maps are also given in the database.

4.2 Geographical distribution

Gabbro, and other basic intrusive or volcanic rock types, constitute a subordinate part of the Swedish bedrock. This is shown by the fact that the 342 basic rock bodies in the database represent a total area of 4400 km^2, corresponding to about 1 % of the area of Sweden.

The locations and sizes of all basic bodies contained in the database are shown in Figure 3. Circles are proportional to the sizes of the different bodies, which ranges from 1 km^2 to 161 km^2.

As seen in the figure, large basic bodies are mainly found in the northernmost part (Norrbotten) of Sweden. A great abundance of relatively small gabbro bodies is also found in the central part (Bergslagen-Värmland) and in the southern part (Småland). Most of these occurrences are considered to be parts of differential series of intrusives of proterozoic age. For some of these occurrences (e.g. hyperites in Värmland), an association with Precambrian subduction zones has also been suggested.

4.3 Shape and depth extent of gabbro bodies

Gabbro mainly occurs in single, well distinguished, rock bodies. Most gabbro bodies are small with surface areas less than 5 km^2, few are larger than 40 km^2. This is apparent in Figure 4 where the distribution of all basic bodies in the database with respect to areal size is shown.

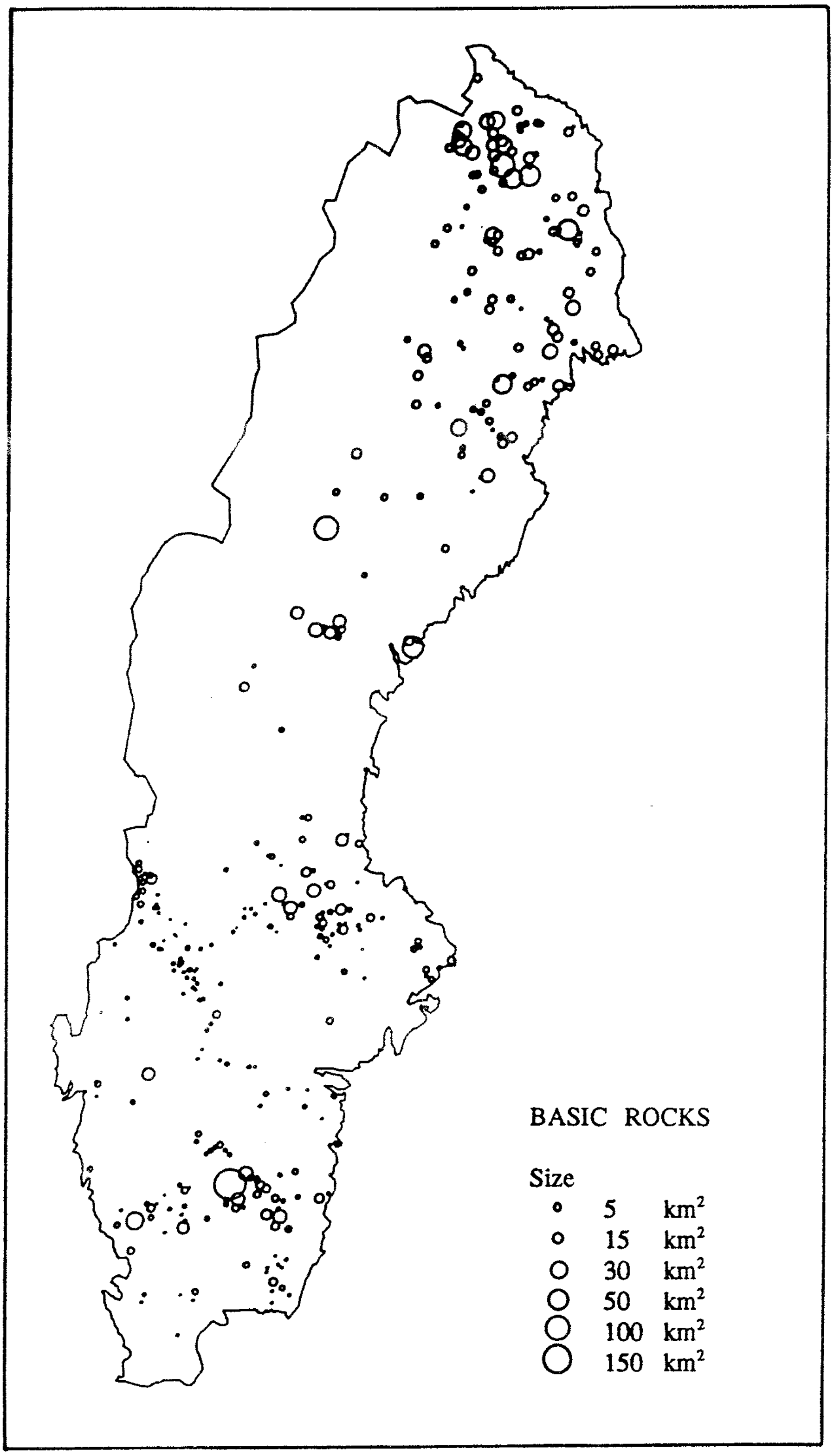

Figure 3. Location of the 342 basic rock bodies identified from the SKB inventory studies. Circles are proportional to the sizes of the rock bodies. The smallest circle represents a 1 km^2 area and the largest represents a 161 km^2 area.

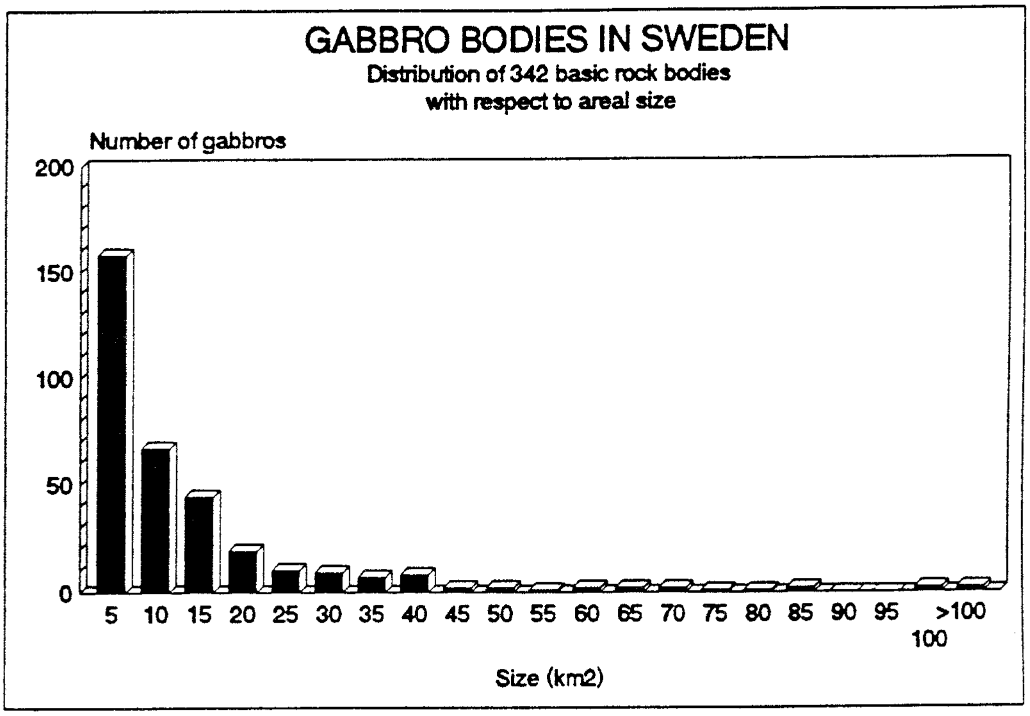

Figure 4. Distribution of basic rock bodies with respect to aerial extension.

Geological mapping, as well as geophysical modelling (Henkel, 1981), show that larger gabbro massifs mostly occur as disk-shaped bodies with horizontal dimensions larger than the vertical extension. To obtain a rough estimate on the relationship between surface area and depth of gabbro bodies, a compilation of results from gravity modelling is presented in Figure 5. The compilation includes depth estimates of 20 gabbro bodies mainly based on Henkel (1981).

As expected, there is a clear tendency for greater depths with larger sizes. The variation is however large, probably due to variable erosional cuts. The variation makes any indirect depth estimate, based on surface area only, highly uncertain. For example, during the year 1983 reconnaissance for gabbro in northern Sweden identified one promising gabbro with a surface area of 12 km^2. It was later found that this gabbro had be subject to drilling by the Boliden Co. Drilling results revealed that the thickness of the gabbro was only 100 m.

However, disregarding these uncertainties, Figure 5 indicates that in order to have some confidence of a 1 km depth for a selected gabbro, a surface area of at least 11-15 km^2 is needed.

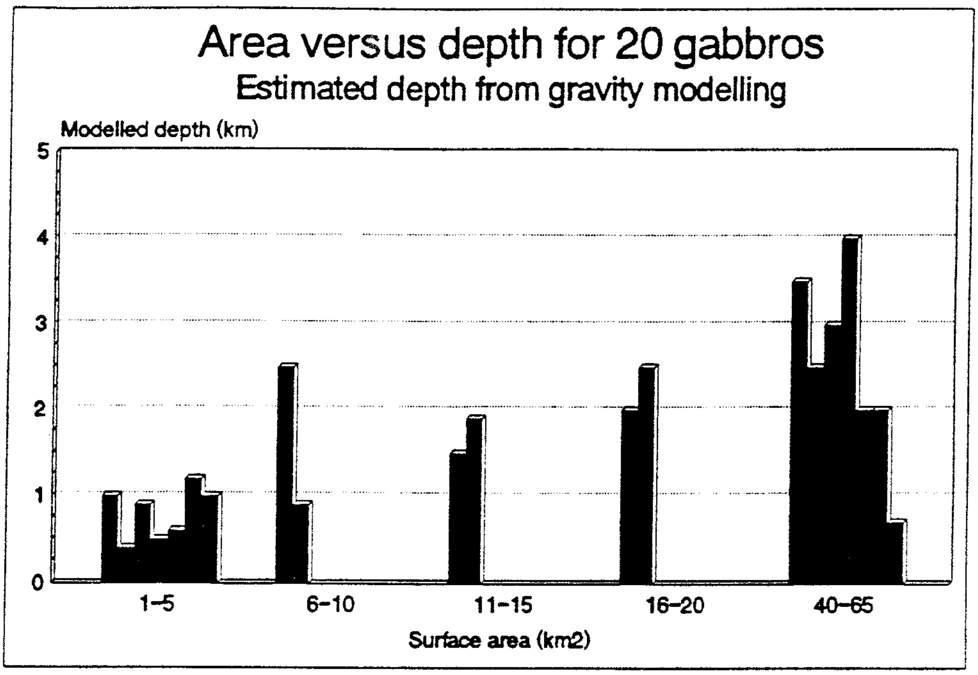

Figure 5. Relationship between mapped surface area of basic rock bodies and their depth as calculated from gravity modelling.

4.4 Implications for site selection

The large horizontal extension of gabbro bodies compared to their vertical dimensions significantly reduces the number of gabbro bodies that can qualify for consideration in a site selection program. As mentioned, a high probability that the depth of a gabbro body exceeds 1 km (which is a postulated requirement in the Swedish program) translates into surface areas being at least 11-15 km^2. In reality, the presence of detrimental features such as fracture zones, faults and dykes, will add further requirements as regards size of the rock body to be selected. Also, factors such as topography and accessibility must be taken into account. Considering all these factors, Swedish experience indicate that a gabbro should have an area of at least 20 km^2 or preferable 40 km^2 to be considered potentially suitable for a repository.

The database contains 54 basic bodies larger than 20 km^2 and 20 bodies larger than 40 km^2 (see Figure 4). Thus, only 16 % and 6 % out of the 342 originally identified gabbro bodies will be suitable for site selection, if the size-criterion is taken to be 20 km^2 and 40 km^2 respectively. This is illustrated by Figure 6, where all gabbro bodies with surface area larger than 20 km^2 are displayed. Considering also non-geological factors such as landownership, population density, alternative use of land etc., adding further constraints, it is understandable why the Swedish programme has failed to select a suitable gabbro body.

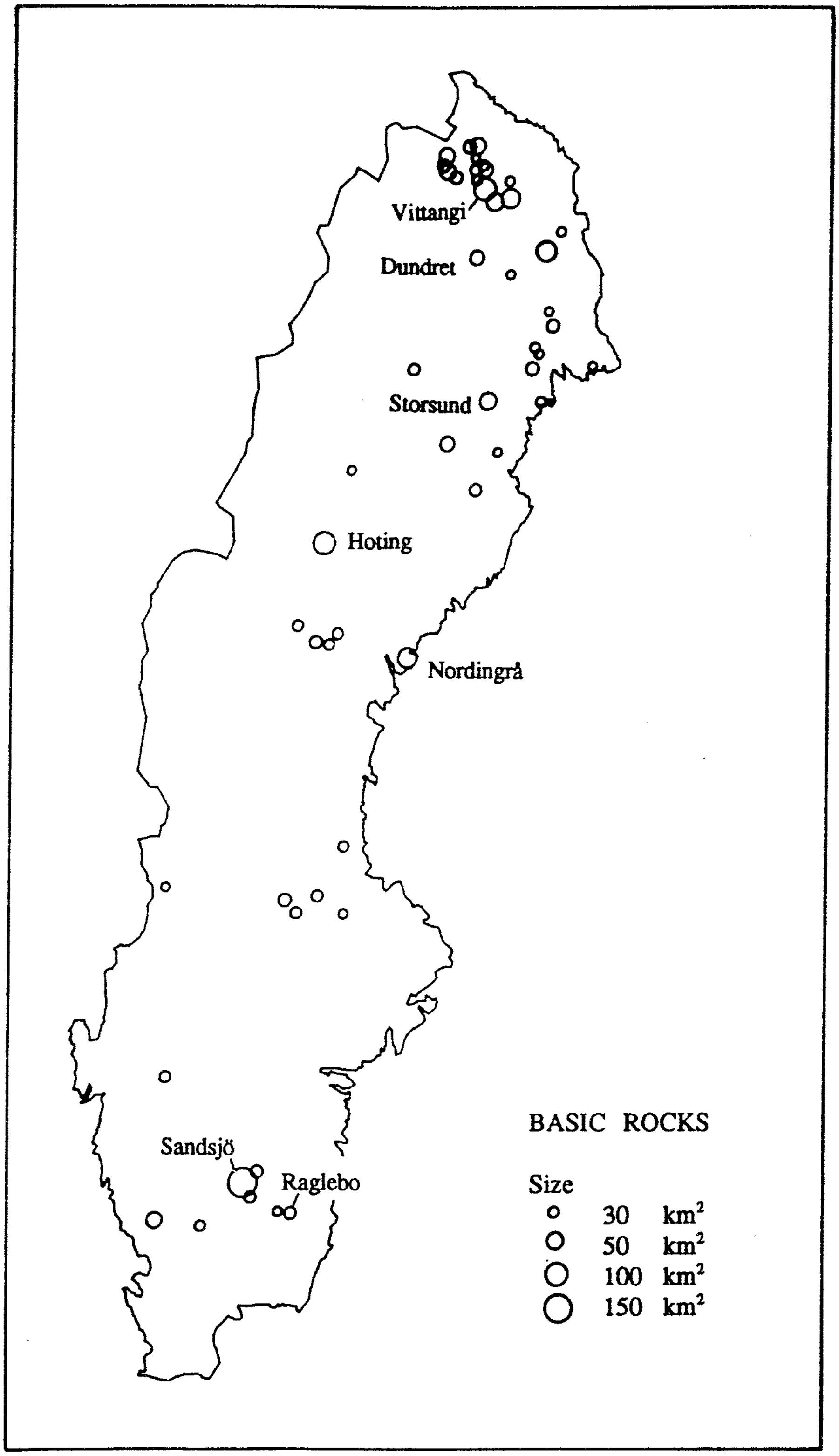

Figure 6. Location of basic rock bodies larger than 20 km^2.

Comparing the distributions shown in Figure 3 and Figure 6 reveals some differences. It is seen that there are very few large basic rock bodies in the southern part of Sweden, in fact only two with sizes exceeding 40 km^2 are found in this region. Instead, the main part of the large gabbros are found in the northernmost part of the country. This region contains 32 out of the 54 gabbro bodies larger than 20 km^2, and 14 out of the 20 gabbros larger than 40 km^2. Thus, considering the distribution of large bodies only, the northernmost part of Sweden is the most favorable region for site selection. However, this region also display several unfavorable non-geologic characteristics, such as accessibility difficulties for site investigations and for transport of nuclear waste. Also, conflicts with alternative use of land (Laplander usage, protected land) can be expected for a large part of this region.

In summary, 342 basic rock bodies with areas of 1 km^2 (anticipated repository area) or more have been identified in Sweden. However, considering the small depths usually found for gabbros and accounting for various kinds of detrimental heterogeneities, the surface area of a gabbro body should be considerable larger, at least 20 km^2. Most of the relatively few gabbro bodies identified that meet this criteria are found in the northernmost part of the country.

5. GEOHYDROLOGICAL CHARACTERISTICS OF GABBRO

5.1 Introduction

It is an established opinion, supported by practical experiences from rock excavation work in civil engineering, that basic rocks are generally poor water conductors. Experiences from mining, representing larger depths, are similar. It is however very difficult to verify these qualitative observations with quantitative measurements of inflows to excavations.

Swedish studies of hydrogeologic conditions at depth, targeted specifically on gabbro formations, are restricted to the borehole investigations of the Taavinunnanen gabbro. Furthermore, hydraulic borehole test data are available from Äspö, where fairly extensive greenstone bodies were encountered during the pre-investigations for the Hard Rock Laboratory currently under development (Wikberg et al., 1991). Results from the investigations at Taavinunnanen and Äspö are briefly discussed below, together with data from Canada and Finland. A more detailed presentation of the work related to Taavinunnanen is given in the Appendix.

The sparse information on geohydrological conditions in gabbro at depth can to some extent be supplemented by data from the near-surface bedrock, which are more abundant. It should be remembered though, that geohydrological conditions at shallow depths may be affected by superficial structural phenomena that need not be present at larger depths. As mentioned earlier, large quantities of data referring to the uppermost 10-100 m exist in the form of water well capacity records. Extensive statistical analysis of this information, aimed specifically at exploring the water bearing characteristics of mafic rocks in relation to other crystalline rock types, have been performed (Liedholm, 1991). Major results are discussed in section 5.3.

5.2 Investigations at depth

Taavinunnanen

Investigations in the deep borehole at Taavinunnanen included conductivity measurements by means of injection tests in borehole sections ranging from 2 m to 100 m in length. Results are further presented in the Appendix. From tests of 100 m sections, bulk rock mass conductivity was found to decrease with depth in the upper 100-200 m, and then to even out at values varying irregularly in the approximate interval $0.5 \cdot 10^{-10}$ to $1 \cdot 10^{-9}$ m/s. Testing using short injection intervals revealed a pattern with large (75-100 m) sections with very low conductivity - typically less than the measuring accuracy, being about $0.5 \cdot 10^{-11}$ m/s. These sections were interrupted by narrow horizons (2-25 m) exhibiting much higher conductivities. Correlation with lithological logging results showed that the high-conductivity parts were strongly correlated to heterogeneous borehole sections, especially the presence of granitic dykes. This is illustrated in Figure 7 which shows hydraulic conductivity as a function of depth, in the form of regression curves (assuming a power-type relationship) treating records from tests in granite sections and gabbro sections as separate data sets. It should be pointed out that the analyses is based on rather few data (see Appendix) and the indicated nature of depth dependency may be more related to the assumed power function and to limitations in measurement accuracy, than to actual correlation of data. The interesting outcome of the analysis is, however that it indicates a conductivity difference of about one order magnitude between the two sampled rock types.

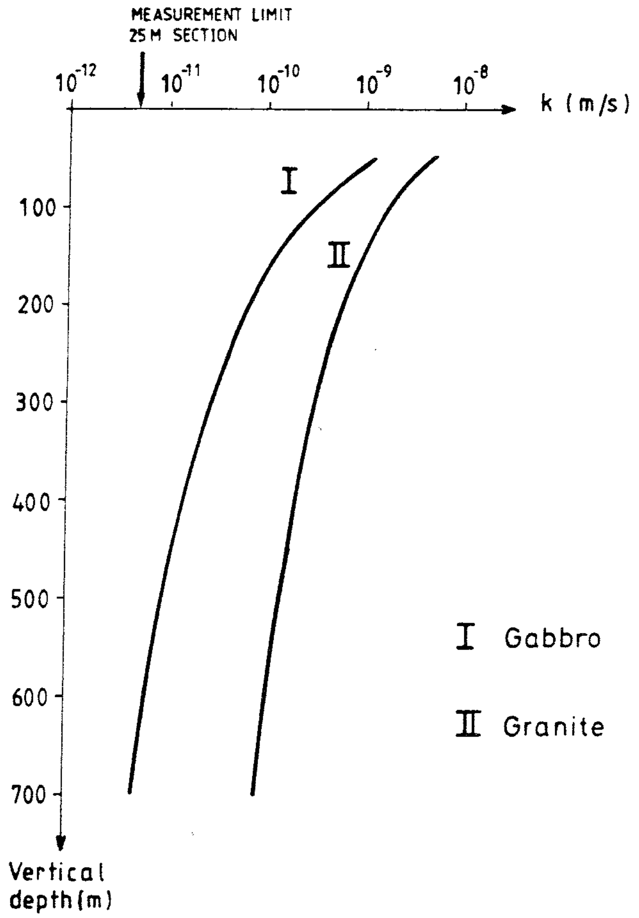

Figure 7. Hydraulic conductivity as a function of depth as measured in the Taavinunnanen borehole. Regression curves (power law assumed) treating tests in gabbro and in granitic dykes as separate data sets (from Gentzschein, 1983).

The results from Taavinunnanen should also be viewed against the general bank of data for non-basic, crystalline rocks. A relevant reference data set for this comparison is the results obtained from SKB's study site investigation program. Figure 8 displays again the regression curves for Taavinunnanen (gabbro and granite dykes) together with corresponding data for granite and gneiss, as obtained from four different sites - Svartboberget, Fjällveden, Kamlunge and Gideå. It can be seen that the gabbro shows 5-10 times lower conductivity than granite/gneiss down to

200-300 m depth. Below this depth, no difference can be observed. This may, to some extent, be a result of the measurement limit. Another result is that the conductivity of the granite dykes at repository depth appears to be anomalously high compared to "average conductivity" for granite/gneiss. It should be recalled again, that data from Taavinunnanen are few - as opposed to the background results from the other sites, which represent a comprehensive data bank. It is possible that comparative analysis of more even sized data sets would indicate even smaller differences.

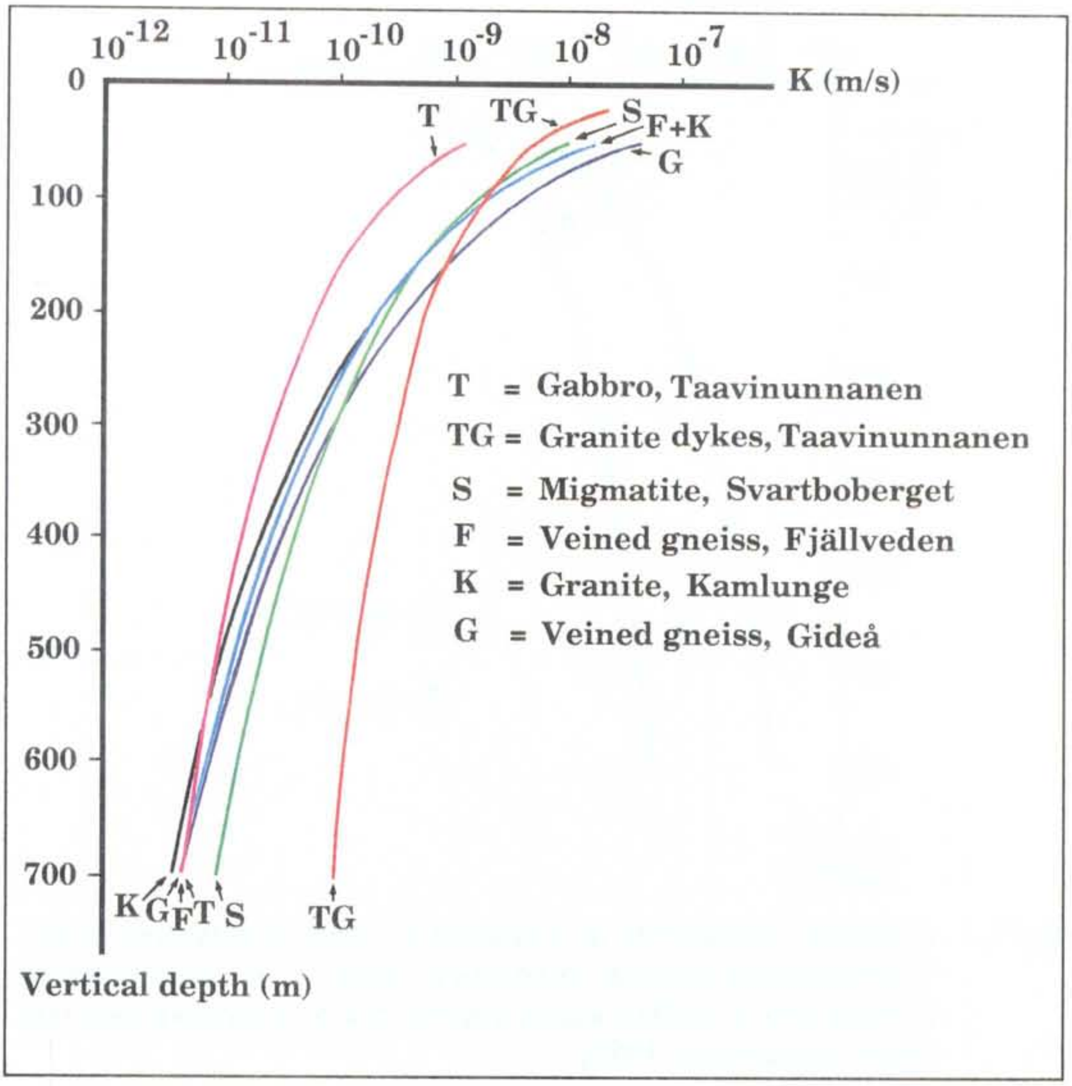

Figure 8. Regression curves for the hydraulic conductivity of gabbro and granitic dykes at Taavinunnanen. For comparison corresponding data from four study sites representing granite and gneiss are also shown (from Ahlbom, 1992).

<u>Äspö</u>

The borehole investigation program at Äspö has included extensive hydraulic injection tests in several boreholes. Rock types include greenstone massifs of diorite - gabbroid composition. Figure 9 shows conductivity data for five rock types, including greenstone, in the form of a Box-and-Whisker plot. The figure illustrates the general conclusion resulting from comprehensive analysis of the data, that there is no simple correlation between rock type and conductivity (Liedholm, 1992). Data for greenstone and diorite are not significantly different from those representing other rock types.

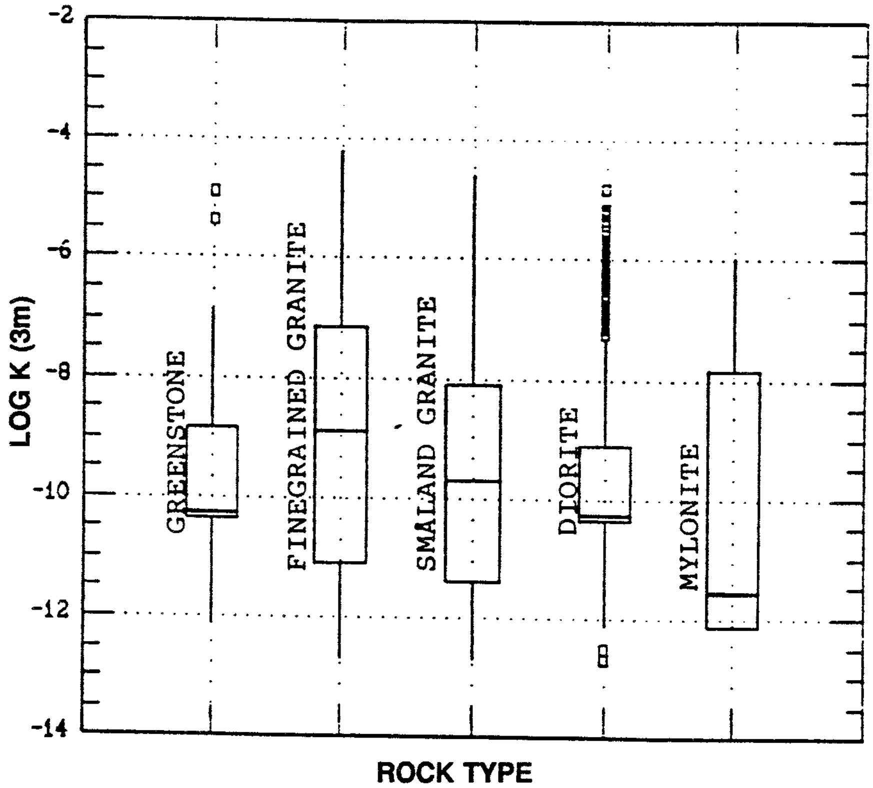

Figure 9. Multiple Box-and-Whisker plot, filtered hydraulic conductivity distribution for different rock types at Äspö. The basis for calculations were the 3-m injection tests in boreholes KAS 02-08 (from Wikberg et al., 1991).

Other studies

Data are also available from the comprehensive investigations of the gabbro-anorthosite intrusion at East Bull Lake in Canada. The permeability was found to range from values around 10^{-8} m/s near the surface to less than 10^{-12} m/s at depths greater than 400-500 m (Raven et al., 1987). As mentioned, the East Bull Lake formation is a layered gabbro, exhibiting major lithological and structural differences between the different layers. Furthermore, fracture frequencies are higher than those obtained from Swedish sites. Geohydrological data from East Bull Lake may therefore not be relevant in the present context.

A geographically and geologically more nearby source of data is the gabbro intrusion near Mäntsälä in southern Finland. Investigations of this gabbro included drilling of two holes down to about 900 m depth (Särkkä, 1990). Conductivities as determined using conventional lugeon-tests, were found to be very low, or below the detection limit of the method. This result refers to the gabbro itself, while intersecting dykes, mostly pegmatites, often showed higher conductivities. The hydraulic tests were, however, made using instrumentation with coarse resolution and rather high lower measurement limit (approx. 10^{-8} m/s). Comparison with hydraulic data from other sites should therefore be made with caution.

5.3 Shallow investigations

As indicated earlier, experiences from underground facilities in mafic rocks indicate low water inflows into the excavations - on average lower than for other crystalline rocks. Experiences from drilled wells are similar, and in this case capacity records allowing quantitative analysis are available.

Ahlbom and Carlsson (1988) compiled results drawn from hydrogeological maps produced by the Swedish Geological Survey (SGU). In these maps, recorded well capacities are interpreted in terms of "regional" conductivity-values. Results from the compilation are shown in Table 3. It appears that basites on average show lower conductivities. However, despite the large geographical areas considered (counties) and resulting relatively large numbers of observations within each area, this trend is not consistent. Another observation is that the reduction in conductivity suggested for the basic rocks, in relation to the other rock types investigated, is a factor of 4 or less. Reflected into a comparative repository performance evaluation context, this would hardly be decisive factor.

In a more comprehensive study using statistical methods, Liedholm (1991) analyzed a large number of well test records with respect to different rock types. Different geographical scales were considered, ranging from a regional scale (10^3-10^4 km^2) represented by counties, to a local scales corresponding to the size of single gabbro plutons. In the regional-scale analysis, well capacity data were referred to a large number of identified rock types. The most frequently represented rock type categories were defined as follows:

Table 3. Compilation of regional hydraulic conductivity in rock drilled wells based on results published in SGU's hydrogeological maps (after Ahlbom and Carlsson, 1988).

County	No. of wells	Median-depth	Regional K-value (x 10^{-8} m/s)			
			Basites	Gneissic granite	Sedimentary gneiss	"Young" granite
Stockholm	198	58	3.9			
	727	58		4.1		
	719	60				5.7
Uppsala	23	45	14.0			
	146	72			4.1	
	103	52				16.0
Södermanland	19	80	2.2			
	1184	65		4.8		
	990	67			3.8	
	197	60				9.7
Västmanland	26	61	4.4			
	303	55			7.5	
	111	54				15.0
Kalmar	44	77	2.6			
	105	54			10.0	
Kronoberg	40	60	15.0			
	46	61		10.0		
	21	55				15.0
Halland	104	65	4.0			

- Gabbro and diorite in gothic environment (target category)
- Småland- and Värmland granites
- Småland- and Värmland granites with augen
- Older granites in the Vetlanda-Oskarshamn area
- Amphibolite in red or greyish gneissic rocks

Some difficulties were encountered in extracting the data representing the rock type under specific study - i.e. gabbro - because the data base available did not clearly distinguish gabbro from diorite. Data were filtered with respect to extreme values. Thus, wells with zero yield were rejected. Similarly, cases where significant water inflow from the overburden, resulting in very high well capacities, were also rejected.

Results from the regional-scale analysis are indicated in Table 4. The table shows data for gabbro/diorite, complied for a total of nine counties. Well capacities (median values) are expressed as specific capacity (m^2/s), here defined as total yield of the well divided by its depth. This parameter is considered to reflect the hydraulic transmissivity of the near-surface bedrock. A statistical ranking procedure was applied to relate the values to the background data set obtained from other crystalline rock types. Results are qualitatively indicated in the table where a low ranking indicates low specific capacity for gabbro/diorite relative to granitic rock types.

Table 4 Condensed capacity data for wells in greenstone (gabbro and diorite), as calculated for nine different counties (from Liedholm, 1991).

County	Specific capacity ($m^2/s \cdot 10^{-6}$), median	Ranking, relative to granitic rocks in general
Södermanland	1.25	low
Stockholm	1.44	low
Kalmar	1.44	low
Halland (amphibolite)	1.71	low
Västmanland	1.82	low
Jönköping	2.29	low - medium
Uppsala	4.01	medium
Blekinge	4.34	medium
Kronoberg	6.02	high

It is clear from the table that well capacities for greenstones tend to fall in the low range, when viewed against data for granitic rocks in general.

Reducing the scale of investigation in a gradual fashion, down to areas corresponding to the lateral extension of individual plutons, generally yielded the same trend with greenstone rocks falling in the low range. Again, however, results where not consistent in this respect. It was also observed that differences between gabbro (or similar rock types) and other crystalline rocks were most pronounced on the regional scale, and successively diminished as the scale was reduced towards single formations. The probable explanation is that the structural setting, in particular fracture zones, has a governing effect on well capacities on a local scale, and that this effect overrides possible differences attributable to rock types. Considering a large enough scale (and correspondingly large sample populations) these local interrelations are averaged out, and rock type specific differences are thus more easily revealed by statistical methods.

Three large gabbro massifs in southern Sweden were selected for detailed study. These massifs were located in the Björnhult area in Kalmar county, Raglebo on the border between Kronoberg and Kalmar, and finally one pluton in the Viserum area mainly in Kalmar but also extending into Jönköping county. For these areas, contour maps were produced by applying punctual kriging technique to the well capacity data. In two of the three cases, a pictorial correlation between the occurrence of the gabbro and low specific water capacity could be established. The contour map for the Raglebo area - which showed the best correlation - is shown in Figure 10.

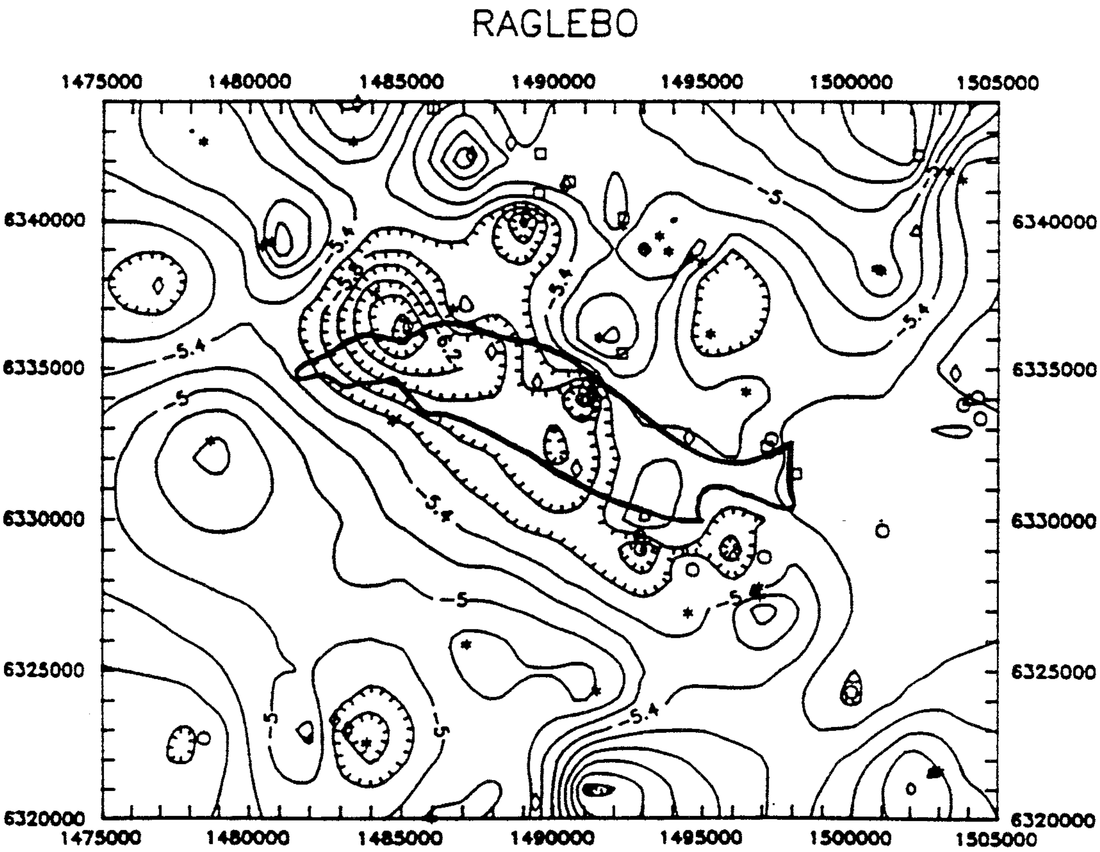

Figure 10. Contour map of specific capacity (mean log10 m^2/s) in the Raglebo area, on the border between Kronoberg and Kalmar counties. Coordinates in meters. The thick line indicates surface extension of the gabbro body.

In summary, the analysis of well test data, generally but not always, shows comparably low water capacities for basic rocks than for granitic rocks. This is in line with well established practical experience. Differences with respect to other crystalline rocks are however at most a factor of about five only, and often much less. Furthermore, it appears that local structural conditions exerts a more governing influence on well capacity then does rock type as such.

5.4 Summary of results

First, it should be recognized that the available data base on hydraulic conductivity in gabbro at depth is limited to tests in one borehole at Taavinunnanen and additional data from other sources, as indicated above. The formal significance of comparisons made with other crystalline rock types is therefore poor. The results obtained by analysis of water capacity records from shallow wells are, on the other hand, based on much more comprehensive data. It should be remembered though, that geohydrological conditions at shallow depths may be affected by superficial structural phenomena that need not be present at larger depths. Furthermore, reservation should be added with respect to possible biases attached to well test data in general.

Despite the above reservations, all available studies reveal a consistent pattern, at least in a qualitative sense. It thus appears that intrusive gabbro bodies are characterized by relatively low conductivity in the gabbro mass itself. Much more permeable horizons are however found coinciding with dykes of different kinds. These dykes appear to be very common in all studied gabbro bodies, spacings typically being of the order of 100 m. Viewed in a repository performance context, this would ruin many of the potential advantages with the low-conductive gabbro mass. Considering conductivity on a larger scale, it is found that gabbro and similar basic rock types are usually somewhat less water conductive than granites and gneisses, but differences are moderate and not decisive in the present context.

6. GEOCHEMICAL CHARACTERISTICS OF GABBRO

6.1 Introduction

This chapter briefly reviews the geochemical characteristics of some gabbroic rock occurrences in Sweden, Finland and Canada with particular emphasis on rock/fracture mineralogy and geochemistry and groundwater chemistry. The Swedish data mainly refer to the Taavinunnanen gabbro, the Finnish data to the Suhanko Ranua, Keminmaa, Sompujärvi and Ylivieska Perkkiönperä areas and the Canadian data to the East Bull Lake gabbro.

6.2 Whole-rock chemistry

Chemically, gabbros contain <54% SiO_2 (little to no quartz is present) which is an indication that they are basic. They have relatively high CaO and Al_2O_3 values reflecting the high plagioclase content, and significant amounts of FeO and MgO representing the presence of the major ferromagnesian mineral components such as pyroxene and olivine (minor amounts of magnetite, ilmenite, biotite and chlorite, when present, also contribute). Representative analyses from some of the classic localities are included in Table 5 for comparison with other areas in Fennoscandia and Canada.

Table 5. Whole-rock chemical analyses of gabbroic rock types (weight percent).

	1.	2.	3.	4.	5.	6.	7.
SiO_2	46.37	50.09	51.12	52.70	46.82	48.7	47.8
TiO_2	0.79	0.14	0.19	0.60	0.18	0.31	0.13
Al_2O_3	16.82	17.49	16.34	17.70	13.51	19.5	20.0
Fe_2O_3	1.52	0.48	1.09	2.42	1.62	9.6	8.4
FeO	10.44	6.04	5.84	5.52	13.50	-	-
MnO	0.09	0.16	0.15	0.14	0.25	0.11	0.12
MgO	9.61	9.11	8.49	-	-	7.9	9.3
CaO	11.29	12.20	13.63	11.30	8.55	11.6	11.3
Na_2O	2.45	2.04	2.18	2.92	0.57	2.8	2.3
K_2O	0.20	0.18	0.06	0.57	0.06	0.20	0.45
H_2O^+	0.38	1.57	0.56	0.50	0.50	-	-
P_2O_5	0.06	0.01	0.03	0.03	0.01	-	-
CO_2	-	0.33	-	-	-	-	-

1. Olivine gabbro; Skaergaard intrusion (Wager and Brown, 1968).
2. Gabbro; Bushveld Complex (Bowes, 1989).
3. Hypersthene gabbro; Stillwater intrusion (Hess, 1960).
4. East Bull Lake gabbro (McCrank et al., 1988).
5. East Bull Lake gabbro (McCrank et al., 1988).
6. Taavinunnanen gabbro; 21.2 m depth (Ahlbom and Larson, 1982).
7. Taavinunnanen gabbro; 700.1 m depth (Ahlbom and Larson, 1982).

6.3 Fracture mineralogy

Larson and Tullborg (1984) reviewed the fracture filling mineralogy common to Swedish metabasites. The term basite is a general term for basic igneous rocks (of which gabbro is an example) and metamorphosed basic igneous rocks. As most basite complexes in Sweden have suffered repeated metamorphism, then the term metabasite has been coined. Metamorphic reactions are important when considering the mineralogy and possible fissure fillings in these rocks. The fracture mineralogy expected to be present in such rock types are clay minerals, chlorite, zeolites and calcite. At a higher metamorphic grade, prehnite, quartz and epidote are to be expected.

The predominance of mafic minerals such as pyroxene, olivine, biotite and magnetite provides a bedrock/groundwater environment which has a rapid and efficient capacity for chemical reduction. Furthermore, the mafic mineral alteration phases (e.g. chlorite, serpentine and Fe-oxyhydroxides) provide a strong sorption capacity for radionuclides. Consequently, radionuclide retardation within the conductive fracture systems of the gabbro should be more efficient than in a granite. Even the presence of titanium may help to scavenge some of the actinides. Moreover, the alteration and breakdown of the Ca-rich plagioclase feldspars to smectite and zeolites, increases considerably the sorption capacity of the gabbro.

An additional important geochemical advantage with basic rock types is the higher cation exchange capacities (CEC) for fracture filling minerals in these rock types compared to granitoids. Although several fracture fillings are common to both rock types, the main difference is the significantly higher CECs for smectite, chlorite and zeolites, which commonly occur in the gabbros, compared to typical granitic fracture minerals such as quartz and calcite. The extreme CEC values for the zeolite minerals (e.g. see stilbite; Table 6) make them particularly important as a natural barrier for the migration of cationic radionuclide species, but only at low temperatures (<85°C) and in a saturated groundwater environment (Smyth, 1982).

Table 6 lists selected ion-exchange capacities as a function of pH for some relevant fracture filling mineral phases and rock-forming minerals. In some important cases there is an increase in the cation exchange capacity (CEC) corresponding to an increase in pH; little difference is observed in the anion exchange capacity (AEC). In particular, note the increase in the CECs (from pH 5 to 8) for limonite, epidote, augite, kaolinite, montmorillonite and biotite.

Table 6. Ion-exchange capacities of some common rock-forming minerals and fracture filling minerals at pH5 and pH8 (after Allard et al., 1983).

Mineral	AEC, meq/kg		CEC, meq/g	
	pH5	pH8	pH5	pH8
Hematite	0.3	0.4	0.2	0.5
Magnetite	0.8	0.5	0.2	0.4
Limonite	3.5	0.7	1.0	6.3
Calcite	-	0.1	-	0.2
Epidote	0.7	0.4	2.8	6.0
Augite	0.2	0.2	4.0	8.0
Hornblende	0.2	0.1	1.8	2.5
Serpentine	-	6.8	0.4	1.0
Kaolinite	0.8	0.6	9.0	28
Montmorillonite	-	0.7	700	800
Biotite	0.4	0.3	6	17
Chlorite	0.3	0.3	50	50
Prehnite	-	0.3	-	25
Quartz	0.1	0.1	0.1	0.2
Bytownite	0.3	0.2	6	9
Stilbite	30	45	630	640
Laumonite	5	3	35	35

AEC = Anion Exchange Capacity CEC = Cation Exchange Capacity

6.4 Hydrochemical characteristics

A compilation of the major ion compositions in the groundwaters from the Taavinunnanen gabbro, East Bull Lake gabbro and the Finnish gabbro occurrences are presented in Table 7. For comparison, the composition of a "typical deep granite water" as defined in the KBS-3 study is also included.

The groundwater data suggest a greater percentage of young, more dilute (low TDS) waters associated with gabbroic rock types when compared to average granitic groundwater compositions. This may be a function of contamination during the drilling and sampling procedures, but may also reflect the hydraulic/ hydrogeochemical conditions particular to gabbroic areas as discussed above. The general absence of dissolved oxygen, together with negative redox potential measurements from the deepest levels in the gabbros, show that reducing redox conditions are established as the young oxidising waters pass through the rock. This is not particularly surprising bearing in mind the mafic composition (and therefore the reducing potential) of both the host rock and some of the fracture filling mineral phases coming in contact with the groundwaters. However, from some of the studied areas such redox changes are not evident until depths of

200-250 m, which is rather worrying from a safety disposal concept. Of course, contamination during sampling cannot be ruled out in some of these cases.

Groundwater data from several of the gabbro sites (Table 7) indicate higher than normal pH values when compared to average granitic/gneissic areas in Fennoscandia.

Table 7. Major ion chemistry of selected groundwaters.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
O_2 (mg/L)	-	0	0.6	0.05	<0.02	0.25	-	-	-	-
pH (field)	7-9	8.8	9.6	9.9	9.8	9.4	6.9	9.7	6.9	8.7
Eh (mV)	0 to -450	-375	+82	+45	-60	+10	+40	-20	-300	+250
Cond. (mS/m)	-	7.6	7.9	-	-	-	20.2	43.5	47.6	33.0
Alkal. (mg/L)	90 to 275	32	30	190	69	149	126	38	326	141
					mg/L					
Ca	10/40	6.5	7.4	2.4	8.5	1.6	23	71	77	16
Mg	2-10	1.4	1.2	0.7	0.3	0.3	8.8	1.2	13	18
Sr	-	0.016	0.019	0.06	0.09	0.06	0.042	0.146	0.10	0.2
Na	10/100	4.1	4.7	76	205	59	5.6	101	5.7	22
K	1/5	0.9	1.3	0.04	0.10	0.3	2.4	2.1	1.6	3.4
Fe(tot)	0.02/5	0.94	1.7	0.56	0.06	<0.04	0.52	<0.05	6.2	0.05
Al	-	0.041	0.048	-	-	-	-	-	-	-
Mn	0.1/0.5	0.018	0.011	<0.02	0.02	<0.04	0.14	<0.02	0.60	0.05
NO_3	.01/.05	<0.04	<0.04	-	-	-	-	-	-	-
SO_4	0.5/15	7.1	5.8	3.5	14.5	6.0	8.8	2.9	6.0	12.0
F	0.5/4	0.11	0.12	<0.1	0.6	<0.1	0.13	0	<0.1	0.13
Cl	4/15	1	<1	17.8	310	1.2	1.6	265	4.2	23
Br	-	-	-	0.17	1.66	0.03	<0.1	2.9	<0.1	0.3
PO_4	.01/.2	0.03	0.06	-	-	-	-	-	-	-
S^{2-}	-	0.04	<0.01	-	-	-	-	-	-	-
^3H (TU)	-	116	156	28	20	26	0.7	0.2	41	17
^2H (‰)	-	-	-	-99.2	-95	-136	-100.3	-99.2	-91.0	-95.9
^{18}O (‰)	-	-13.8	-13.8	-13.5	-13-3	-17.8	-14.04	-13.92	-13.02	-13.2

1. Typical ranges for Swedish groundwaters in granitic bedrock (KBS-3)
2. Taavinunnanen (KS-590); level 493 m (Laurent, 1984)
3. Taavinunnanen (KS-558); level 651 m (Laurent, 1984)
4. East Bull Lake (EBL-1); level 204-213 m (Bottomley et al., 1989)
5. East Bull Lake (EBL-2); level 504-642 m (Bottomley et al., 1989)
6. East Bull Lake (P5); level 88.5-97.6 m (Bottomley et al., 1989)
7. Suhanko, Ranua (YP-128); level 540 m (Blomqvist et al., 1986)
8. Suhanko, Ranua (YP-128); level 580 m (Blomqvist et al., 1986)
9. Keminmaa, Sompujärvi (Ki-23); level 275 m (Blomqvist et al., 1986)
10. Ylivieska, Perkkiönperä (R-313); level 350 m (Halonen et al., 1990)

6.5 Implications for radionuclide transport

The geochemistry of the gabbros promotes the formation of fracture filling mineral phases which have a high cation-exchange capacity (e.g. smectite, chlorite and zeolites) and a high absorbance capacity (e.g. Fe-oxyhydroxides, Ti-bearing alteration products). The presence of fracture clay phases (e.g. smectite), which are generally highly expandable in the presence of water, results in many of the fractures becoming self-sealing.

Rapid flow along specific hydraulic fractures precludes, in some cases, long residence times and therefore the natural geochemical evolution of the groundwaters by rock/water interactions (e.g. ion-exchange mechanisms). Consequently, the groundwaters are often of a dilute near-surface character, sometimes relatively young (tens of years in the case of Taavinunnanen), and may even penetrate to considerable depths. Alternatively, or as contributory factor, rapidly recharging oxygenated aggressive waters may, over a long period of time, have removed all the leachable components in the fractures, thus preserving the low TDS character of the groundwaters and reducing the overall redox buffering capacity of the bedrock at shallow depths.

Highly saline groundwaters at depth were not detected at Taavinunnanen. Their occurrence at East Bull Lake was not considered to be the result of rock/gabbro interactions over very long periods of time, but rather the result of groundwater reactions occurring deep in the adjacent country rocks and being slowly transported into the gabbro environment along the regional hydraulic gradient. In contrast, the Finnish saline water occurrences are believed to be the result of gabbro/water interactions at depth during long residence times.

7 GEOMECHANICAL CHARACTERISTICS OF GABBRO

7.1 Introduction

In assessing the geomechanical and rock engineering characteristics of gabbro, it is important to observe that the structural geological situation often exerts a larger influence on rock mass mechanical behavior than does the rock type as such. In the present context, the premise is that we are interested in what conditions are to be expected in a gabbroic body, selected on the basis of criteria including uniformity and good rock quality. Interpretation of experience available from actual rock engineering efforts in tunnelling and mining must be made with this in mind. The fact that these case studies represent gabbro does not necessarily imply that they represent a relevant geomechanical environment. This is especially true for mines, which are the only excavations known to have been created in gabbro at depth.

As mentioned earlier, data on the geomechanical and rock engineering characteristics of gabbro have been gathered from a wide variety of sources. The compilation draws on basic data from the literature, as well as on estimates of rock mass characteristics and qualitative experiences from mining- and tunnelling efforts in gabbro rocks. The site investigations conducted at Taavinunnanen and Mäntsälä constitute major sources of information from which the rock mass parameters of relatively undisturbed gabbro intrusions have been derived. Civil engineering projects in gabbro are much less common than in granite or gneiss. Information is however available from tunnelling objects in the Gothenburg area and also from defense-related facilities (Ludvig, 1991). Mines in mafic environments, providing important insight into rock engineering conditions at depth especially with respect to stability conditions, are found in Finland (Lindholm, 1991) and in Canada (Swan, 1991).

7.2 Rock stress conditions

No documented rock stress measurements in Swedish gabbro formations have been conducted. In Finland, however, a number of gabbro sites have been subject to stress determinations (Särkkä, 1990, Lindholm, 1991). Data from these sites have been reviewed, and are illustrated in Figure 11. Otanmäki, Vuorokas and Kotalahti are mines located in mafic environments. Besides gabbro, they represent a number of mafic rock type, though within mechanically similar regimes.

The parameter plotted in Figure 11 is the maximum horizontal stress. The condensed-form results obtained from the mentioned sites have been overlaid on a large quantity of background data. These data have been extracted from the comprehensive data base compiled by Stephansson et al. (1987) and contain all observations available from measurements in precambrian rocks in Scandinavia.

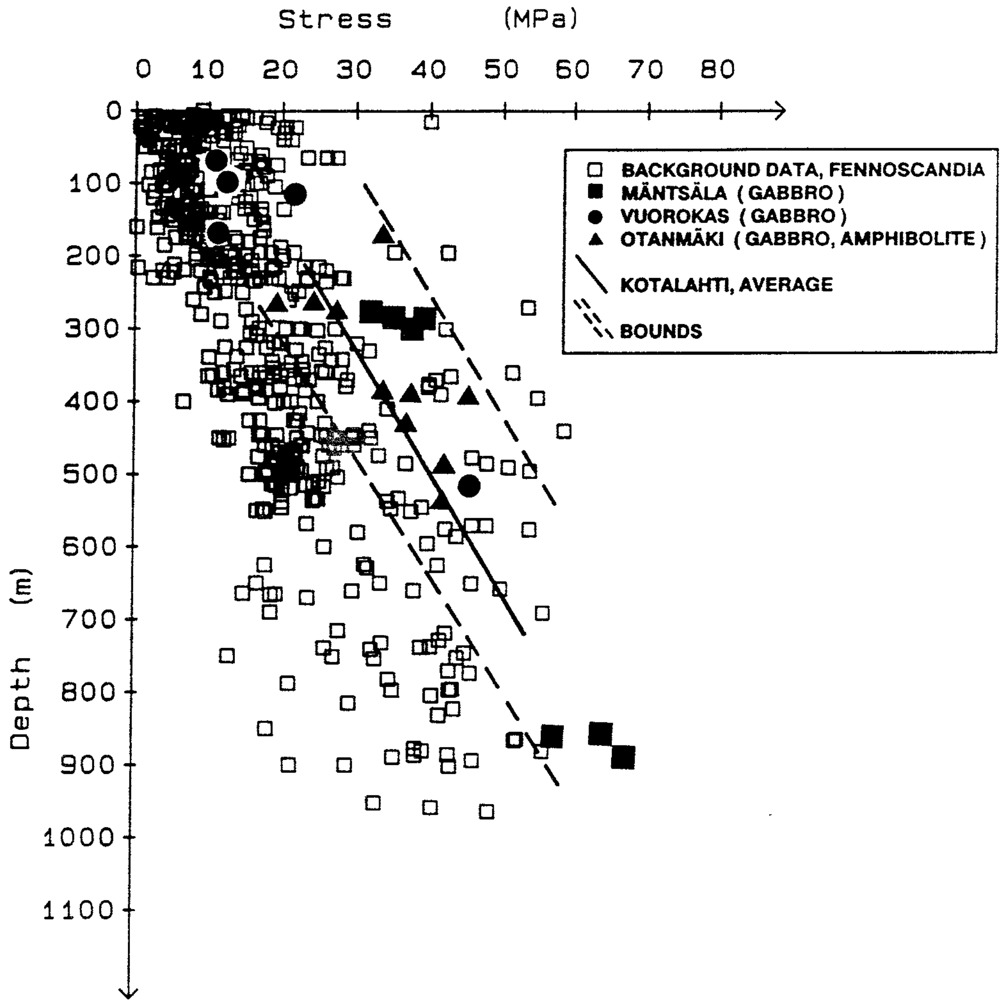

Figure 11. Maximum horizontal stress plotted versus depth. Background data include all observations available from the Fennoscandian Shield. Data for gabbro are from four locations in Finland. Approximate bounds refer to observations in gabbro.

Excluding i) the uppermost 200 m, and ii) a few observations of extremely high stresses in the background database, the stresses measured in gabbro formations are found towards the upper bound of the range for the total data set. This can be seen in the figure, despite the large scatter of data. The rate of increase with depth is 0.060 MPa/m for the gabbro-data, to be compared with 0.044 MPa/m, which is the gradient obtained when including all data from Fennoscandia. The data refer to the maximum horizontal stress only. Analysis with respect to other stress components yields, of course, different numbers but in fact very similar trends. The observed stress anomaly attached to the gabbro-data has not been subject to any statistical examination. In fact, prior to conducting any such analysis, it would be necessary to in detail scrutinize the data with respect to their experimental background - an effort which is outside the scope of the present study. Instead, we rely upon direct observation of the data available, in combination with judgement. The conclusion that gabbro formations exhibit high rock stresses is still believed to be valid, not least because of the fact that it is remarkably well supported by practical experience from the referred mines, where indications of high stresses are common at moderate depths. There are a number of more or less plausible explanations for the indicated excessive stress conditions:

- Density; The higher density translates into proportionally higher vertical stresses. The effect on the horizontal stresses is theoretically less pronounced, but may be significant if creep mechanisms related to glaciation is a contributory source of the present stress field.

- In comparison to their surroundings, gabbro intrusions are stiff rock masses. In a continuum loaded by boundary stresses (such as the bedrock if viewed on a large enough scale) stiffer parts will be subjected to higher stresses than softer parts.

- In comparison to their surroundings, gabbro intrusions are high strength rock masses, that can carry large stresses before self-adjustment by large scale deformation processes occurs.

- Remnant stresses related to the geological processes forming the gabbro intrusions.

7.3 Fracture frequency

A substantial amount of core drilling for metal prospecting purposes has been conducted in mafic intrusions at a number of location in central- and northern Sweden. Documentation of joint frequency from these efforts is generally not available, but qualitative observations indicate that tectonic disturbances have often been absorbed by the surroundings of the mafic intrusions. Zones bounding the intrusions, and occasionally also intersecting dykes, are therefore heavily fractured, while the inner parts of the mafic bodies are preserved very intact.

A detailed fracture frequency diagram from the deep borehole at Taavinunnanen is given in the Appendix. Figure 12 shows the same data, transformed to averages for 100 m sections, and also corresponding data from the two deep boreholes at Mäntsälä in southern Finland. For comparison, the overall trend (average and approximate range of variation) derived on the basis of a large quantity of data representing essentially granite and gneiss are overlaid in the same figure. These background data have been extracted from investigations at four Swedish study sites. Neglecting individual sections with higher fracture frequency, it is seen that the observations in gabbro tend to fall below, or in the lower part of the range representing gneiss/granite. A definitive difference can however not be concluded on the basis of available data. The rate of decrease in fracture frequency with depth appears to be similar for both categories.

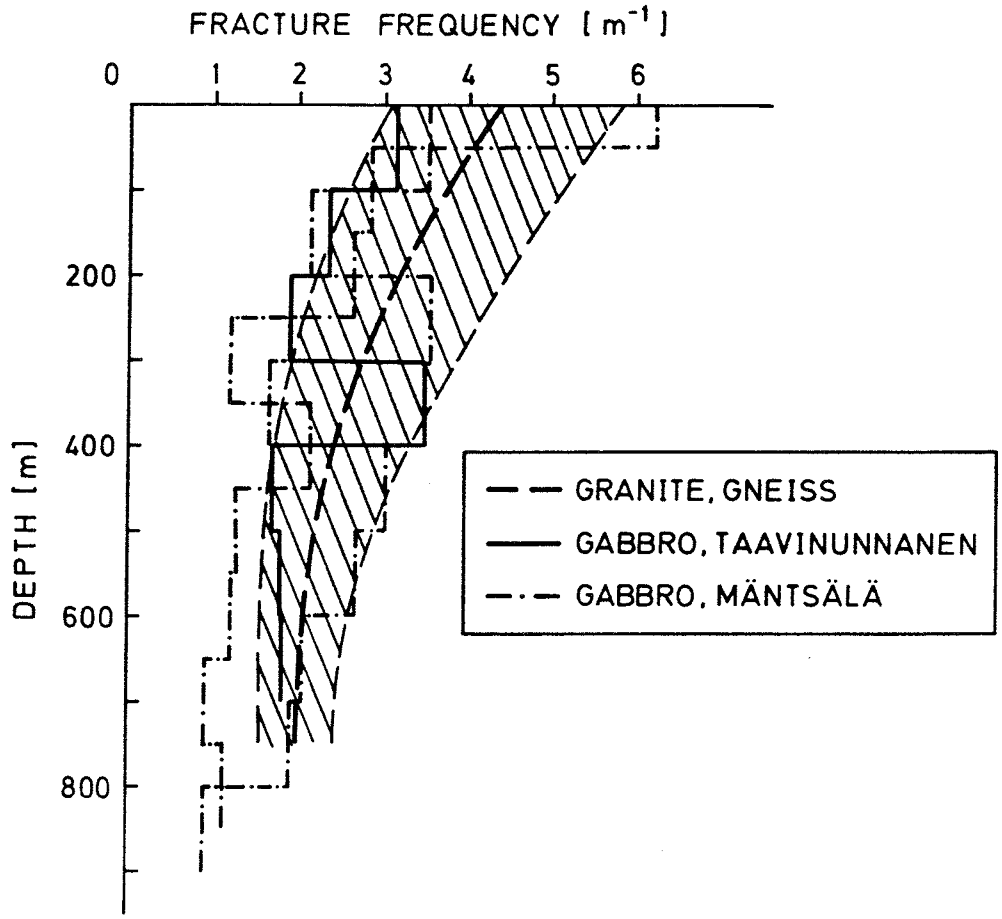

Figure 12. Fracture frequency as a function of depth. Histograms show data obtained from gabbro intrusions (Taavinunnanen and Mäntsälä). Shaded area shows average and approximate range of variation for granitic rocks at Swedish study sites.

It should be observed that the averaging procedure applied effectively smooth out local peaks in fracture density, which are often responsible for a large portion of the total fracture count. In gabbro, such peaks were found to often occur in connection with intersecting dykes. This applies to both Taavinunnanen and Mäntsälä. The fracture density in horizons with uniform gabbro can therefore be substantially lower than the numbers indicated in Figure 12.

7.4 Mechanical properties of joints

With the possible exception of some case studies, no data collection exists on mechanical properties of joints in gabbro rocks. One reason is that classification of joint mechanical behavior is normally not done with respect to rock type, which would be irrelevant in practical application, bur rather with respect to the joint properties as such.

Deformability- and strength properties of rock joints are strongly influenced by tectonical history and chemical environment. From chemical considerations, one would expect a larger portion of the joints to be filled and healed in gabbro than in, for example, granitic environments. This would reflect into comparably higher strength in gabbro.

7.5 Deformability and strength

Intact samples of gabbro rocks generally exhibit high stiffness and strength, c.f Table 1. Results from a compilation of a large quantity of data on Young's modulus of elasticity are shown in Figure 13. For comparison, the approximate distribution for granitic rocks is indicated in relative form. It is seen that the distributions overlap, but that the difference in mean is significant.

As for most other rock types, the compressive strength of gabbro, as determined by standard laboratory methods, shows a wide scatter. Values recorded ranges roughly from 100 MPa to more than 350 MPa and averages some 280 MPa, which is higher than for most other crystalline rocks. Compact norite can exhibit extremely high strength.

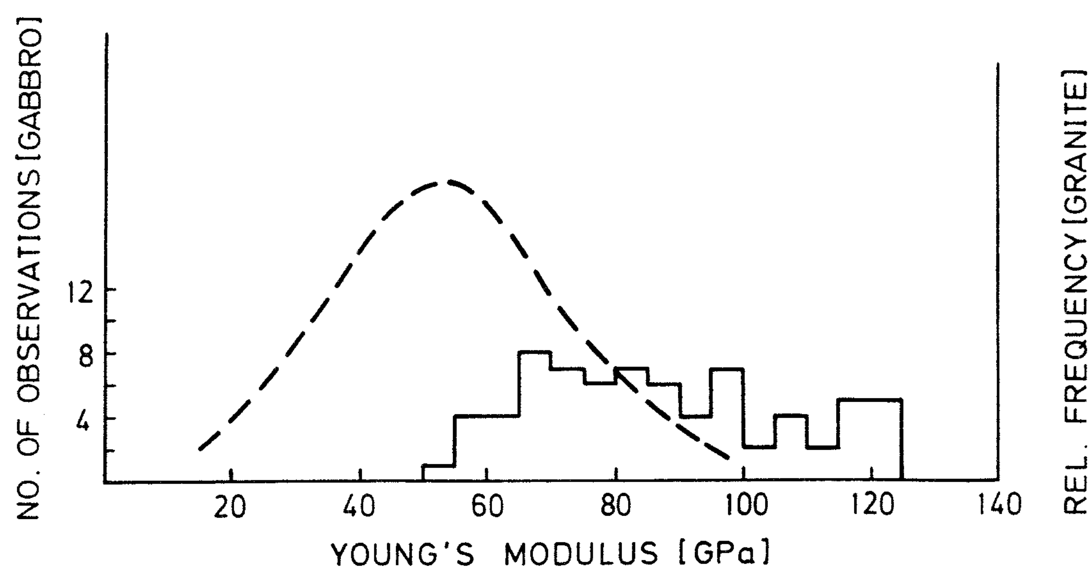

Figure 13. Data on Young's modulus of gabbro (histogram) and approximate frequency distribution for granitic rocks (dashed curve).

Figure 14 illustrates the above parameters in the form of a typical stress-strain curve obtained from a uniaxial compression test of a gabbro specimen. A comparison with the corresponding curve for a granitic specimen, also shown in the figure, gives that the gabbro has higher stiffness and higher strength. Other features of gabbro that can be observed in the diagram include linear deformation behavior up to failure, and brittle failure characteristics. As will be discussed later, these characteristics have implications on excavation stability.

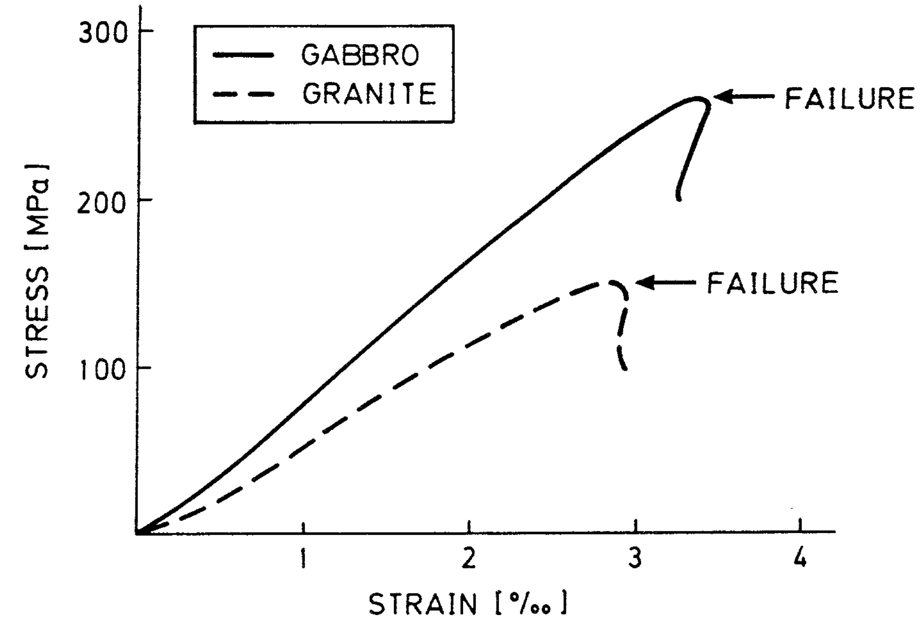

Figure 14. Typical stress-strain curves for gabbro and granite specimens tested in uniaxial compression.

The above results refer to intact rock samples. The deformability and strength of rock masses, however, result from contributions from both the intact rock and from discontinuities. It is heavily influenced by the geometrical distribution, stiffness and strength of the joints.

For crystalline rock of good quality, rock mass deformability, as determined in the field in connection with excavation work at depth, typically falls in the range 35-70% of the values for intact rock specimens. For granites, this roughly corresponds to values of 15-50 GPa. Data for gabbro, referring to the rock mass scale, are not available. Crude estimates using empirical relationships give deformation modulus values in the range 40-70 GPa, assuming joint frequencies as indicated for gabbro at depth, and an intact-specimen modulus of 80 GPa.

A gabbro intrusion would thus generally have higher stiffness than a typical granitic surrounding. Estimates of the strength of gabbro rock masses also indicate high values, as compared to crystalline rocks in general.

7.6 Excavation stability

The generally low degree of tectonical impact, sparse jointing and high strength exhibited by gabbro formations translates into a favorable material from a construction viewpoint. Applying rock classification procedures, verified in engineering practice, to the data available typically yields quality rankings in the upper extreme range for crystalline rock masses. This is illustrated in Table 8, which shows estimates expressed as index values in commonly used classification systems.

Table 8. Typical rock mass quality designation values for gabbro rocks, as obtained using common rock classification systems (averages for Taavinunnanen and Mäntsälä).

Classification system	Index value	Description
RQD	90-100	Excellent rock
Q-system	100-400	Very/extremely good rock
RMR-system	80-95	Very good rock

Very good stability conditions would thus be expected. An important reservation must, however, be added; It has been shown that gabbro formations exhibit high stresses, at least at depth. This implies that excavations may experience stress-related instability problems, that occur despite good rock quality. Furthermore, material properties of gabbro include high strength- and stiffness, good elasticity and brittle failure behavior, c.f Figure 14. These characteristics promote accumulation of large quantities of recoverable strain energy around excavations. Failures, initiated by high stresses, may under such conditions occur suddenly, and can involve violent spalling from the excavation periphery. This is a form very local, excavation-induced rock bursts.

It is thus relevant to consider excavation stability for conditions of low rock stresses and high rock stresses separately, since stability conditions may differ significantly. In terms of practical experiences, low stresses translate to shallow excavations, and high stresses correspondingly to excavations at depth.

Shallow excavations (low rock stresses)

Data on stability conditions and related reinforcement measures are available from tunnelling projects in Gothenburg, and also from defense-related facilities in gabbro, involving excavation of considerable rock volumes. In summary, very good stability conditions are reported. As for other high-quality crystalline rocks, instabilities observed are usually gravity-controlled fall-outs of isolated blocks, formed by intersecting fractures. Blasting generally results in good excavation contours, which further promotes good stability. Reinforcement requirements are typically limited to sparse bolting. Shotcreting is rarely needed to maintain stability, except when passing through intersecting fracture zones or dykes, which can exhibit drastically lower rock quality than the overall rock mass.

Excavations at depth (high rock stresses)

Practical experiences from deep excavations in gabbro originate exclusively from mines, since no other excavations are known to have been created at depths exceeding 200 m. It should again be emphasized that mines typically represent structurally disturbed conditions, that may differ significantly from those of concern in the present context.

Keeping this in mind, interpretation of data from mines in gabbro (and similar) environments in Finland and Canada generally show good stability conditions, provided that rock stresses are not critically high. Instability related to high stresses is, however, not uncommon at depths of the order of 500 m, and can occasionally occur in the form of violent spalling. The possibility of this form of instability occurring in tunnels excavated in massive gabbro at depths of about 500 m (and more) can thus not be excluded. The modes of excavation instability observed under high stresses are highly dependent on extent and nature of pre-existing fracturing. In more fractured ground, the deformation process is gradual, and sudden spalling does not occur.

Reinforcement measures to control minor or moderate stress-controlled failures in massive rock is bolting, often in combination with meshes or shotcrete. Timing of reinforcement installation with respect to the successive development of deformations behind the tunnel face is important. This complication may retard tunnel advancement.

7.7 Drilling and blasting

Available experience from conventional, percussive drilling in gabbro formations can be summarized as follows:

- Penetration rates are often lower for gabbro than for granite or gneiss. This is due to the high strength and high toughness of gabbro. The average difference is however of the order of 10-20% only. This is similar to the range of variation for each rock type. Accurate predictions require site specific data.

- Problems with wear of drill bits are less pronounced in gabbro than in granite, due to the lower quartz content, which is the decisive parameter with respect to abrasivity. In effect, the much lower abrasivity of gabbro is to some extent balanced by the lower penetration rate, and in terms of drill bit life the difference averages some 25% in favor for gabbro.

Experiences from full-face tunnel boring and raise boring are similar. In the full-face case, however, effects attributable to rock type are often overruled by factors related to structural conditions. The very high penetration rates that occasionally are reported from full-face tunnelling in mafic rocks appear to be linked to intensely fractured formations. For sparsely fractured gabbro, penetration rates would be expected to be similar or somewhat lower than for a granite of comparable quality.

Considering blasting characteristics, one would expect gabbro to be highly resistant to any kind of dynamic breakage, including blasting, given its intrinsic properties (high density, strength and toughness). In full scale, however, blasting characteristics are also strongly influenced by extent and type of preexisting fractures, and damping characteristics of the rock mass. Gabbro generally offers favorable characteristics in these respects. The overall conclusion is that gabbro falls in a the medium range in terms of blastability.

Another, and more important, observation is that gabbro of good quality allows a well controlled blasting operation, resulting in little overbreak and limited blast damage. Although quantitative comparisons do not seem to be available, experience quite consistently shows that less blast damage can be achieved in gabbro than in granite/gneiss. This opinion is well established in both mining and tunnelling. Reducing blast damage generally improves tunnel stability and reduces rock reinforcement needs. In the present case, it may also affect repository performance, since the "disturbed zone" hydraulic transmissivity will depend on the blast damage situation.

8 GABBRO AS A REPOSITORY HOST ROCK

Previous chapters have summarized the existing geoscientific knowledge of gabbro, of relevance in a repository context. This chapter elaborates on the "pros and cons" of gabbro as a host rock for a repository, considering site selection, feasibility of repository construction, and finally post-closure repository performance.

8.1 Site selection

Availability of gabbro bodies

Gabbro bodies constitute a small part of the Swedish bedrock. Neglecting occurrences with surface areas less than 1 km^2, it is found that gabbro intrusions cover in total about 1 % of the area of Sweden. The gabbro intrusions are typically disc-shaped, with a vertical extension that is considerably smaller than the horizontal. Gravity modelling indicates that in order to expect the depth of a gabbro body to be 1 km or more, a surface area of 10 km^2 or more should have been documented. As was discussed in section 4.4, gabbros are typically intersected by faults, fracture zones and dykes - features that should be avoided when locating a repository. This will add to the size requirement on gabbro bodies that could be considered as potentially suitable for a repository.

Considering the above factors, it appears that only bodies with large areas can provide the required vertical and lateral degrees of freedom in the siting procedure. Swedish experience indicate that a surface area of at least 20 km^2, and preferably 40 km^2, would be required. The probably rather complete information available on Swedish gabbro occurrences shows that there are only a few tens of gabbro bodies of this size within the country. Out of these, the majority are remotely located in the northernmost part of Sweden.

Thus, it is obvious that gabbro, in comparison to granitic rocks, offers a much more limited selection of rock bodies that meet the primary criteria of having a size large enough to host a repository. Considering also constraints added by non-geological factors such as accessibility, alternative use of land, landownership, population density etc., it is believed that few gabbros, if any, would in reality be acceptable for a repository.

Ore potential

An overview of the ore potential in gabbro has been presented by Brotzen (1985). Compared to gneisses and granites, economically interesting deposits occur more frequently in gabbro and other basic rock types. There are three main types of ore deposits. The largest are titaniferous iron deposits, holding potentially minable grades of iron, titanium and vanadium. Swedish examples are Smålands Taberg and Akkavare (Grip, 1973). The large size of these deposits make them rather easy to discover and to avoid.

The second type is iron-copper-nickel sulphide ores. These deposits tend to be more irregular in distribution, and rather small deposits might be minable. They are difficult to discover, since they often occur near the base of the gabbro bodies. In Sweden there are many deposits of this type, although most of them are, with today's metal prices, not of economic interest. A typical example is the deposit at Lainijaur in the Västerbotten county (Grip, 1961) which was mined for a short period in the 1940's. Figure 15 shows a profile through the mine.

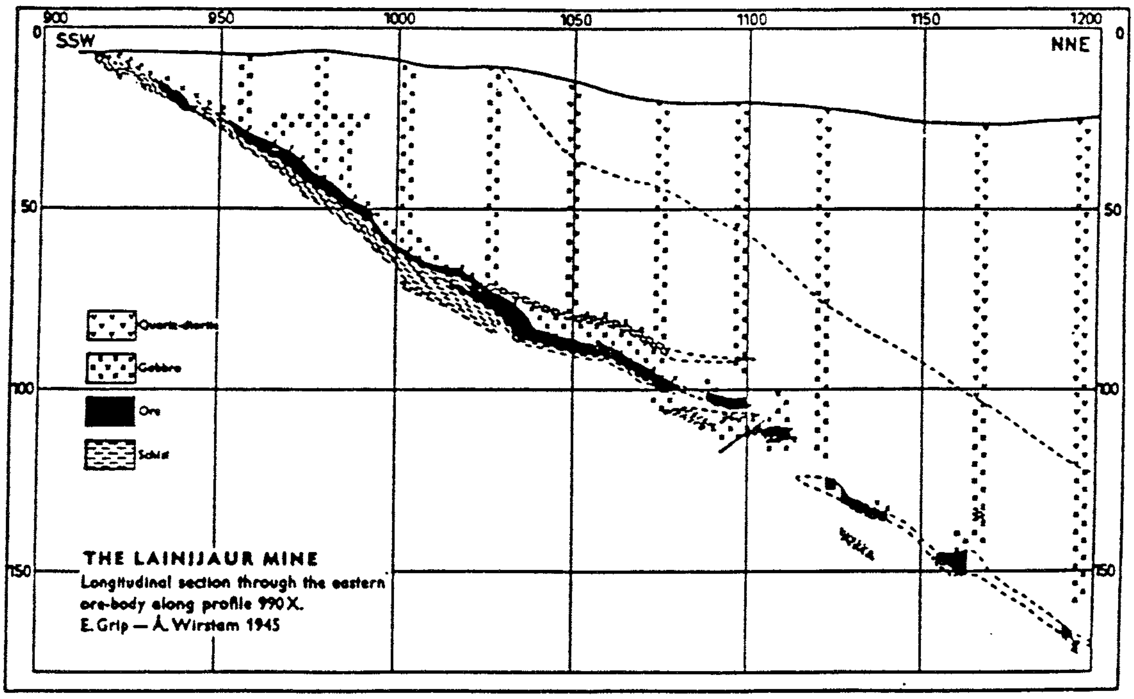

Figure 15. Profile through the Lainijaur nickel mine (from Grip, 1961).

The third type are the platinum deposits, of which wellknown occurrences are found in South Africa. No such deposits have been discovered in Sweden, but in fact no systematic prospecting has been conducted for this type of ore deposits.

In summary, there is a higher potential for ore deposits, as defined on the basis of current economical criteria, in gabbro compared to granite and gneiss. For some of these deposits, drilling is the only way to obtain information regarding their occurrence. In a long term perspective, a more general definition of "ore potential", as anomalously high concentrations of any mineral and/or presence of very rare minerals, seems more relevant. Even with this definition, however, gabbro would hold a larger ore potential, not least because of the much more limited occurrence in comparison to granitic rocks. The risk for future "intrusion" is therefore larger for a repository situated in gabbro than for a repository in more abundant, granitic rocks.

8.2 Repository construction

Intrinsic characteristics of gabbro include high strength and high stiffness - typically higher than for granitic rocks. In the rock mass scale, gabbro formations are found to be sparsely fractured. At depth, the fracture frequency typically fall in the range 1-3 fractures per meter. This is similar to, or slightly lower than averages extracted from the SKB study sites in granite and gneiss. Significant local anomalies in fracture frequency are often observed in connection with dykes that intersect the gabbro intrusions, whilst undisturbed regions can exhibit almost intact gabbro.

From a rock engineering viewpoint, sparse fracturing in combination with high strength implies good quality rock mass. Gabbro can therefore be expected to offer good construction feasibility with regard excavation stability and water inflows. Drilling, (conventionally or using full-face technique), blasting, reinforcement and rock sealing will not meet any serious obstacles. In these respects, no decisive differences are found in comparison to high-quality, granitic and gneissic rock masses. Practical experiences from construction work in gabbro rocks at shallow depth verify these findings. As in other crystalline rocks, dykes and fracture zones intersecting gabbro bodies can locally alter construction conditions significantly, and cause temporary problems in controlling mechanical stability or water inflows. With respect to ventilation requirements during construction, gabbro may offer some advantage in comparison to granitic rock types, because the generally lower natural radioactivity will eliminate possible problems with health hazards related to excess radon levels.

At depth, gabbro formations are characterized by high rock stresses. Available data from stress measurements in gabbro bodies in Finland show values in the upper part of the range typical for Scandinavian bedrock. In massive, sparsely fractured rock masses with brittle failure characteristics, such as gabbro, high stresses can alter construction feasibility, in terms of inducing stress-related excavation instability. These phenomena may even occur in the form of violent spalling of the rock surrounding the excavation. Excavations available in gabbro at depth are limited to mines, where the structural conditions are often disturbed. Thus, the geomechanical conditions may not be comparable to those found in more intact gabbro. Experiences from these mines, however, clearly support the finding that high stresses can cause stability problems at depths of about 500 m. The occurrence of similar phenomena during repository development in gabbro can, although unlikely, not be excluded. It is also a general experience from excavation work in crystalline rocks that stress-driven stability problems are often locally enhanced near dykes and faults.

In summary, it is difficult to provide a general comparative estimate between gabbro and granitic rocks, as regards stability conditions at depth. Considering average rock properties for the two rock types, gabbro is more liable to the indicated type of problems related to high stresses. In a specific case, however, structural conditions may have a more governing influence than the rock type as such.

8.3 Repository performance

The proposals to consider gabbro as an alternative to granite and gneiss for hosting a repository have been supported by arguments mainly relating to post-closure repository performance. In summary these arguments have been:

- The lower water capacity of gabbro and other basic rock types, as observed in drilled wells, will restrict groundwater circulation and thus retard potential radionuclide transport;

- The different chemical environment in gabbro offers potentially significant advantages in terms of high sorption capacity;

- The high mechanical competence of gabbro promotes tectonical stability.

Below, these factors are discussed, in the light of present knowledge in the field, as presented earlier in the report. Some comments relating to the thermo-mechanical conditions in the post-closure phase are also given.

<u>Hydrogeological conditions</u>

Comprehensive analysis of well test records with respect to rock types show that gabbro and other basic rocks often but not always have lower water capacity than granitic rocks. Generally speaking, the variation in specific capacity attached to each rock type is large, as compared to the indicated differences between rock types. In fact, no specific rock type can be claimed to consistently exhibit low transmissivity. This applies even when large sample areas such as counties are considered. The study of well capacity data also showed that indicated differences between gabbro (or similar rock types) and other crystalline rocks were most pronounced on the regional scale, and successively diminished as the scale was reduced towards single formations.

These results strongly suggest that the structural setting, in particular fracture zones, has a governing effect on well capacities on a local scale, and that this effect tend to override possible differences attributable to rock types. Considering a large enough scale (and correspondingly large sample populations) these local interrelations are averaged out, and rock type specific differences are thus more easily revealed by statistical methods.

An important observations from the studies of well data is that the reduction in regional average conductivity suggested for the basic rocks, in relation to the other rock types investigated, is a factor of five or less. Reflected into repository performance evaluation on a more local scale, this would hardly be decisive factor. Finally, a reservation must in the present context be added to results derived from well tests, because they refer to shallow depths where conditions are affected by superficial structural phenomena that need not be present at depth.

The available data base on hydraulic conductivity in gabbro at depth is limited to tests in one borehole at Taavinunnanen and some additional data from other sources. The formal significance of comparisons made with other crystalline rock types is therefore poor.

The hydraulic tests in the Taavinunnanen borehole generally showed low hydraulic conductivities in sections with fresh gabbro. Rather high hydraulic conductivities were however measured in connection with granitic dykes. Judging from the few observations available, the difference averages about one order of magnitude. A few conductive sections were also found at deformed and chlorite-altered gabbro sections. Comparing the data from the Taavinunnanen gabbro with results from other SKB study sites representing gneiss and granite, indicates a lower conductivity for the gabbro down to about 200-300 m.

Summarizing data from all investigations available, they indicate somewhat lower conductivity for gabbro than for granitic rocks. Data are however not consistent. The differences indicated would not be decisive with respect to repository performance.

The studies involving investigations at depth, however, reveal a qualitatively consistent pattern as regards the occurrence of dykes intersecting the gabbro bodies. Such dykes are common in all studied gabbro bodies, and typically occur with spacings of the order of 100 m. Not surprisingly, they seem to be characterized by much higher conductivity than the gabbro mass itself. Acting as major groundwater conduits, these features would, in a repository situation, also constitute the major pathways for potential radionuclide transport. Thus, much of the potential advantages with the low conductivity and favorable chemistry of the gabbro itself may be ruined by such heterogeneities. If frequently occurring they could be a decisive factor that disqualifies a rock body from further studies.

On the other hand, subhorizontally oriented, hydraulically conductive features can under certain circumstances be favorable since they may act as "hydraulic barriers", thus preventing or reducing vertical groundwater circulation by removing hydraulic gradients due to local topography. The lithological boundaries formed by the horizontal or gently dipping layering often found in gabbro bodies may provide such conditions.

Geochemical conditions

The mineral chemistry of gabbro poses some potentially rather important advantages as compared to granitic rocks. The presence of pyroxene, as well as its alteration product chlorite, implies a high cation exchange capacity. The high percentage of these minerals in gabbro, in combination with a high amount of iron (II) and titanious minerals, will probably cause a strong sorption of radionuclides. This is even more so due to the high sorption capacities found in zeolite minerals and in smectite clays, both common fracture fillings in gabbro.

The database on hydrochemical conditions in gabbro at depth is very limited. The samples available show waters that are often of a near-surface dilute character. This is possibly due to rapid flow along a few highly conductive fractures. The groundwater samples at Taavinunnanen indicate that young waters (tens of years) have penetrated to considerable depth. No saline water was found in the Taavinunnanen borehole. However, saline water was found in some Finnish gabbro massifs.

As discussed earlier, the groundwater flow in gabbro bodies seems to be controlled by relatively few, highly conductive structures, often associated with granitic dykes. In effect, this can reduce or eliminate the advantages associated with the fracture mineralogy of gabbro, since short residence times may preclude complete development or rock/water interaction. The presence of swelling clay minerals in gabbro promotes self-healing processes of fractures. This is regarded as a positive effect, since it will restrict groundwater flow in the rock mass. However, it may in fact also contribute to further concentrate the groundwater movements to intersecting, granitic dykes.

In summary, it appears that the differences in geochemical conditions between gabbro and granitic rocks can potentially be more important in a repository context than possible differences in the hydrological or mechanical environment. However, resulting effects in terms of repository performance have not been verified experimentally, and no definitive conclusions can be drawn in this respect.

Bedrock stability

The intrusion of large gabbro bodies is accompanied by deformation of the surrounding bedrock. This is often clearly seen on airborne magnetic maps. For example, interpretation of data from Taavinunnanen showed that the gabbro body is surrounded by a 3 km wide deformed zone. As a result of this phenomena, and of the high mechanical strength of gabbro, later crustal movements are sometimes observed to be largely absorbed around the intrusive contacts of the gabbros with the country rocks, rather than penetrating the body itself. This resistance to crustal activity is of course a potential advantage from a repository performance viewpoint. The significance of this argument must however be assessed in each particular case, on the basis of site specific information.

Thermomechanical conditions

In the postclosure phase, a repository is subjected to mechanical loadings from several sources, including the preexisting stress field, thermomechanical loads and possibly also forces associated with glaciation and seismicity. Because of the differences in thermal and mechanical properties between gabbro and granitic rocks, the thermomechanical effects are of special interest in the present case.

Besides by rock properties, the thermomechanical load is influenced by several engineered parameters. However, considering only the general case, the lower thermal conductivity- and diffusivity of gabbro will translate into higher temperatures and sharper thermal gradients in the rock surrounding a canister/repository in gabbro than in granite. The induced thermal stress field is a function of both the thermal field and some of the mechanical parameters. Comparing again with granite, the higher temperatures attained in gabbro also implies higher stresses. The high rock mass stiffness of gabbro is another factor that will contribute to the stress generation. To some extent, however, the equation can be balanced by the coefficient of thermal expansion; The lower values of this parameter often encountered for basic rocks will translate into correspondingly lower thermal stresses.

Combining all these factors yields that higher thermal stresses are to be expected in gabbro than in granite, given that all engineered system parameters are identical. A crude estimate, based on typical values of rock properties and simplifying assumptions as regards rock mass thermomechanical behavior, indicates that the difference is a factor of about 1.5 (Leijon, 1991).

To obtain the total stress field, the thermal stresses should be superimposed to the preexisting stress field. The high in-situ stresses often observed in gabbro formations will therefore further enhance the difference between gabbro and granite in terms of post-emplacement rock stress situation.

Depending on repository system, the higher stresses may or may not have significant implications on repository performance. The perhaps most important, negative effect that can be envisaged is the possibility of stress-induced failures occurring in the near-field of deposition excavations, due to the combined effects of high preexisting stresses and superimposed thermal loading. This can influence near-field, thermal - and hydraulic conductivities. In this particular respect, gabbro is a less favorable host medium than granite. On the other hand, it appears that the effects of the moderate rock type related differences, if desired, can relatively easy be compensated for by means of design parameters such as depth to the repository, thermal source power output and spatial canister distribution. This will negatively affect repository volume requirements and costs, but hardly to any critical extent.

9 MAIN CONCLUSIONS

With respect to the feasibility of selecting a site for a repository, there are obvious disadvantages associated with the gabbro-alternative. This is because the number of gabbro bodies available in Sweden, that have sufficient size to appropriately host a repository is limited, probably to a few tens. Out of these the majority are found in the northernmost part of the country. An important factor in this context is the fact that gabbro intrusions typically have much larger surface areas than depth extensions. Furthermore, the required flexibility to avoid major structures within the selected rock body imposes additional volume requirements.

Thus, in a site selection situation presuming gabbro, the number of potentially suitable locations would be very limited from start. Adding further discriminating factors of non-geological character, such as accessibility, alternative use of land, landownership and population density, it is believed that few gabbros, if any, would in reality be acceptable for siting a repository.

Considering then the construction of a repository, no decisive difference in conditions offered can be identified, when comparing gabbro to granitic rocks. Generally speaking, both rock types provide good construction feasibility and, in fact, poses similar problems related to large-scale structural features. In a particular case, site specific structural conditions are likely to have a larger influence on construction feasibility, than actual rock type. The potential problems associated with stress-induced instability of excavations at depth should be observed in this context. Because of high in-situ stresses and massive rock mass characteristics, gabbro may be more liable to such problems than granite.

With respect to repository performance, it is clear that the mineral chemistry of basic rocks offers potential advantages as compared to granite/gneiss. This includes high sorption capacity and potential for self-healing of fractures. The significance of these processes is, however, not well verified experimentally.

Available data on the hydraulic conductivity of gabbro show, on average, somewhat lower values than for granite/gneiss. Results are, however, not consistent. Furthermore, the differences indicated are typically a factor of five or less, which is not decisive with respect to repository performance. An important characteristic displayed by all gabbro bodies investigated, is that they are rather frequently intersected by granitic dykes. These are often highly fractured and exhibit higher hydraulic conductivity than the gabbro host rock. Thus, in the large scale corresponding to the size of a repository, they would constitute the major groundwater conduits and consequently also the major pathways for radionuclide transport. This phenomena may reduce or eliminate the potential advantages associated with both the chemical environment and the low conductivity of gabbro.

The relatively poor thermal energy transport capacity of gabbro implies some disadvantages, in terms of higher thermomechanical loads on the rock in the post-closure phase. Differences with respect to granitic rocks are however moderate. It is envisaged that they can, if desired, be balanced by design measures. This will however negatively affect repository volume requirements and also costs.

In conclusion, there are obvious difficulties associated with siting a repository in gabbro, due to lack of sufficiently large gabbro bodies. In comparing gabbro with granitic rocks, no decisive differences can be demonstrated on the basis of the present state of knowledge, neither with respect to repository construction, nor as regards repository performance.

10 REFERENCES

Ahlbom K., Henkel H., Scherman S. and Tiren S., 1980: Rekognoserande studier för typområden i mellersta och norra Norrland under 1979-1980. Rapport PRAV 4.22.

Ahlbom K. och Olkiewicz A., 1981: Rekognoserande studier för typområden i Västernorrlands och Norrbottens län, 1980-1981. Rapport PRAV 4.31.

Ahlbom K., Larson, S-Å. och Olkiewicz A., 1982: Borrkärne- och ytkarteringsresultat från Taavinunnanen gabbron. SKBF/KBS AR 82-55.

Ahlbom K. and Carlsson L., 1988: Sammanställning av olika bergarters vattenförande egenskaper baserade på undersökningar för lagring av kärnavfall. Symposium om grundvattenförsörjning den 4:e maj 1988. VIAK AB och Svenska Hydrologiska Rådet.

Ahlbom K., 1992: Gabbro as a host rock for a repository. Swedish experiences. SKB LOK 92-02.

Alapieti T.T. and Lahtinen J.J., 1986: Stratigraphy, petrology, and platinum-group element mineralisation of the early Proterozoic Penikat layered intrusion, northern Finland. Econ. Geol., 81, 1126-1136.

Albino B., 1984: Borrhålsgeofysiska undersökningar och parametermätningar från borrhålet i Taavinunnanen. SKBF/KBS AR 84-24.

Allard B., Karlsson M., Tullborg E-L. and Larson S-Å., 1983: Ion exchange capacities and surface areas of some major components and common fissure filling minerals of igneous rocks. SKBF/KBS, Technical Report 83-64.

Alm B., Alm O. och Röshoff K., 1984: Basiska bergarters mekaniska och fysikaliska egenskaper - en litteraturstudie. Högskolan i Luleå, Avd. Bergmekanik, 1984:13.

Almén K-E., Andersson J-E., Carlsson L. och Hansson K., 1982: Hydrauliska tester i berg. Del 4: Jämförande studier av olika hydrauliska tester. SKBF/KBS Arbetsrapport 83-02.

Ambros M., 1980: Beskrivning till berggrundskartorna Lannavaara NV, NO, SV, SO och Karesuando SV och SO. Sveriges Geologiska Undersökning. Af 25-30.

Blomqvist R., Lahtinen R., Lahermo P., Hakkarainen V. and Halonen S., 1986: Geochemistry of deep groundwaters in bedrock in Finland: Results of the investigations in 1986. Geol. Surv. Finland, Nuclear Waste Disposal Res., Rep. YST-53.

Bottomley D.J., Gascoyne M. and Kamineni D.C., 1990: The geochemistry, age, and origin of groundwater in a mafic pluton, East Bull Lake, Ontario, Canada. Geochim. Cosmochim. Acta. 54, 933-1008.

Bowes D.R., 1989: Igneous and metamorphic petrology. Encyclopedia of Earth Sciences (Ed. R.W. Fairbridge), Van Nostrand Reinhold, New York.

Brotzen O., 1985: Gabbro som förvarsbergart. SKBF/KBS AR 85-06.

Brown A. and Kamineni D.C., 1987: A reconnaissance survey of structures at the East Bull Lake Pluton, Ontario. AECL, Tech. Rec. TR-348.

Bååth M., 1983: Earthquake Data Analyses. An example from Sweden. Earth Science Reviews 19, 181-303. Elsevier Science Publishers.

Eriksson B. and Hallgren U., 1975: Beskrivning till berggrundskartbladet Vittangi NV, NO, SV, SO. Sveriges Geologiska Undersökning. Af 13-16, 1-203.

Gentzschein B., 1983: Hydrogeologiska undersökningar i Taavinunnanen gabbron. SKBF/KBS AR 84-25.

Gentzschein B. and Tullborg E-L., 1985: The Taavinunnanen gabbro massif. A compilation of results from geological, geophysical and hydrogeological investigations. SKB TR 85-02.

Grip E., 1961: Geology of the Nickel Deposits at Lainijaur in Northern Sweden. Sveriges Geologiska Undersökning, C 577.

Grip E. och Frietsch R., 1973: Malm i Sverige 2. Almqvist & Wicksell, Stockholm.

Gulson B.L., 1972: The precambrian Geochronology of granitic rocks from northern Sweden. Geologiska föreningen i Stockholms förhandlingar, 94, 229-244.

Hallgren U., 1979: Berggrundskartorna Soppero NV, NO, SV, SO. Sveriges Geologiska Undersökning. Af 31-34.

Halonen S., Hakkarainen V., Blomqvist R., Lahermo P. and Tuula L., 1990: Geochemistry of deep groundwater in bedrock: Results of the investigations during 1987-89. Geol. Surv. Finland, Nuclear Waste Disposal Research. Rep. YST-65.

Henkel H., 1981: Stora gabbro intrusioner i norra Sverige. Kompletterad version. Sveriges Geologiska Undersökning, Sektionen för regionalgeofysik. Rapport 8110. 44-51.

Henkel H., Hult K. and Eriksson L., 1983: Neotectonics in northern Sweden - geophysical investigations. SKBF/KBS Technical Report 83-57.

Hess H.H., 1960: Stillwater igneous complex, Montana. Mem. Geol. Soc. Am. 80.

Kamineni D.C., McCrank G.F.D., Stone D., Ejeckam R.B. and Sikorsky R., 1985: A preliminary report of alteration and fracture-filling mineralogy in the East Bull Lake pluton, District of Algoma, Ontario. In: Current Research, Part B. Geol. Surv. Canada, Paper 85-1B, 81-88.

Kamineni D.C., 1986: A petrochemical study of calc. amphiboles from the East Bull Lake pluton anorthosite-gabbro layered complex, District of Algoma, Ontario. Contr. Miner. Petr., 93, 471-481.

Kamineni D.C., 1987: Halogen-bearing minerals in plutonic rocks: a possible source of chlorine in saline groundwater in the Canadian Shield. In: Brines and gases in crystalline rocks (Eds. P.Fritz and S.K. Frape); Geol. Assoc. Can.Spec. Paper 33.

Klasson H., Leijon B. and Ljunggren C., 1990: Neste Oy gas storage program - Rock stress measurements at the Mäntsälä investigation area. Report. Renco AB, Luleå, Sweden.

Larson S-Å., 1980: Layered intrusions of the Ulvö dolerite complex, Ångermanland, Sweden. PhD dissertation. Publ. A 36, Geologiska Institutionen, Chalmers Tekniska Högskola och Göteboregs Universitet.

Larson S.Å., Olkiewicz A., Ahlbom K. and Ålinder C. 1984: A tentative model of the Taavinunnanen gabbro - results from a core drilling. Geologiska föreningen i Stockholms förhandlingar 106 (2).

Larson S-Å., and Tullborg E-L., 1984: Fracture fillings in the gabbro massif of Taavinunnanen, northern Sweden. SKBF/KBS TR 84-08.

Laurent S. 1984: Analysis of groundwater from a borehole in Taavinunnanen. SKBF/KBS AR 84-36.

Leijon B., 1992: Geomechanical and rock engineering characteristics of gabbro. SKB LOK 92-01.

Liedholm, M., 1991: Combined evaluation of geological, hydrogeological hydrochemical and geophysical information 1. SKB PR 25-89-03.

Liedholm M., 1992: The hydraulic properties of different greenstone areas. SKB LOK 92-07.

Lindholm O., 1991: Pers. comm.

Ludvig B., 1991: Pers. comm.

McCrank G.F.D., Kamineni D.C., Ejeckam R.B. and Sikorsky R., 1988: Geology of the East Bull Lake gabbro-anorthosite pluton, Algoma District, Ontario. Can. J. Earth Sci., 26, 357-375.

McNutt R.H., Gascoyne M. and Kamineni D.C., 1987: The $^{87}Sr/^{86}Sr$ values in groundwater of the East Bull Lake pluton, Superior Province, Ontario. Appl. Geoch., 2, 93-101.

Magnusson N.H., 1973: Malm i Sverige 1. Almqvist Wicksell, Stockholm.

Nurmi P.A., Kukkonen I.T. and Lahermo P.W., 1988: Geochemistry and origin of saline groundwaters in the Fennoscandian Shield. Appl. Geoch., 3, 185-203.

Pulkkinen J. and Frii J., 1985: Sublevel stoping in Kotalahti Mine -A case history. Proc. Symp. Large Scale Underground Mining, Lulå, 1985. Centek Publishers, Luleå, Sweden, pp 145-156.

Raven K.G., Lau j.s.o., Ejeckam R.B., Smedley J.A., Sweezey R.A. and Sikorsky R.J., 1985: Borehole geologic and hydrogeologic investigations ar the East Bull Lake Research Area. AECL Tech. Rec. TR-299, 200-219.

Raven K.G., Bottomley D.J., Sweezey R.A., Smedley J.A. and Ruttan T.J., 1987: Hydrogeological characterisation of the East Bull Lake research area. Environment Canada, IWD Sci. Series, No. 160; NHRI Paper No. 31, 77p.

Ruth T., 1984: Equilibrium calculations for water-mineral interactions at the Taavinunnanen test site. Swedish Geological Company. Internal report 84001.

SKBF/KBS, 1982: Radioactive Waste Management Plan, PLAN 82. SKBF/KBS TR 82-09.

SKB, 1986: R&D-programme 86.

SKB, 1989: R&D-programme 89.

SKN, 1987: Management and disposal of spent nuclear fuel. Review of a program for research, development and other measures. (Granskning av FoU-program 86).

SKN, 1990: Evaluation of SKB R&D programme 89.

Smellie J.A.T. 1983: Groundwater pump flow rate and its effect on some physico-chemical parameters - A controlled experiment carried out at Taavinunnanen. SKBF/KBS AR 83-45.

Smellie J.A.T., 1992: Gabbro: Geological and hydrogeochemical features. SKB LOK 92-03.

Smyth J.R., 1982: Zeolite stability constraints on radioactive waste isolation in zeolite-bearing volcanic rocks. J. Geol. Vol. 90.

Stephansson O., Myrvang A., Dahlström L-O., Fjeld O.K., Bergström K., Hanssen T.H., Särkkä P. and Väätäinen A., 1987: Fennoscandian rock stress data base. Research Report TULEA 187:06, Luleå Univ. of Technology, Luleå, Sweden.

Stigh J., 1982: Ultramafiter i svenska delen av fjällkedjan - möjlig slutförvaringsplats för radioaktivt avfall? Rapport till Svensk Kärnbränsleförsörjning AB.

Streckeisen A., 1976: To each plutonic rock its proper name. Earth Sci. Rev. 12.

Sundberg J., 1988: Thermal properties of soils and rocks. Ph. D. Thesis A 57, Department of Geology, Chalmers University of Technology and University of Göteborg, Gothenburg, Sweden.

Swan G., 1991: Pers. comm.

Särkkä P., 1990: Rock mechanics surveys in site selection for natural gas storage in Finland. Proc. Rock Mech. Meeting, Swedish Rock Engineering Research Foundation, Stockholm. pp 85-100 (in swedish, summary in english).

Tiitola M., 1990: Modelling of survey areas for natural gas storage cavern and rock engineering analysis. Thesis, Department of Materials Science and Rock Engineering, Helsinki University of Technology, Helsinki, Finland, 57 pp (in finnish, summary in english).

Teollisuuden Voima Oy (TVO), 1990: Plan for research into basic rock types. TVO Work Report 90-45.

Wager L.R. and Brown G.M., 1968: Layered igneous rocks. Edinburgh: Oliver and Boyd.

Welin E., 1970: Den Svekofenniska orogena zonen i norra Sverige - En preliminär diskussion. Geologiska föreningen i Stockholms förhandlingar 92, 433-451.

Wikberg P. (ed), Gustafson G. and Stanfors R., 1991: Äspö Hard Rock Laboratory. Evaluation and conceptual modelling based on the pre-investigations 1886-1990. SKB Technical Report 91-22, Stockholm.

APPENDIX

THE TAAVINUNNANEN GABBRO

This report shows that there exist a rather good knowledge regarding the distribution, shape and geological characteristics of Swedish gabbro massifs. However for "hard data" on the geological, geohydrological and hydrochemical characteristics of gabbro at depth, there is only one source of information in Sweden - the 700 m deep borehole in the Taavinunnanen gabbro massif. Results from the investigations of this borehole have been presented in several chapters of this report, though in a fragmented form. This appendix provides an overview of the investigations at the Taavinunnanen gabbro, including process of selection of the site, scope of investigations and main results. The location of the Taavinunnanen gabbro is shown in Figure A1.

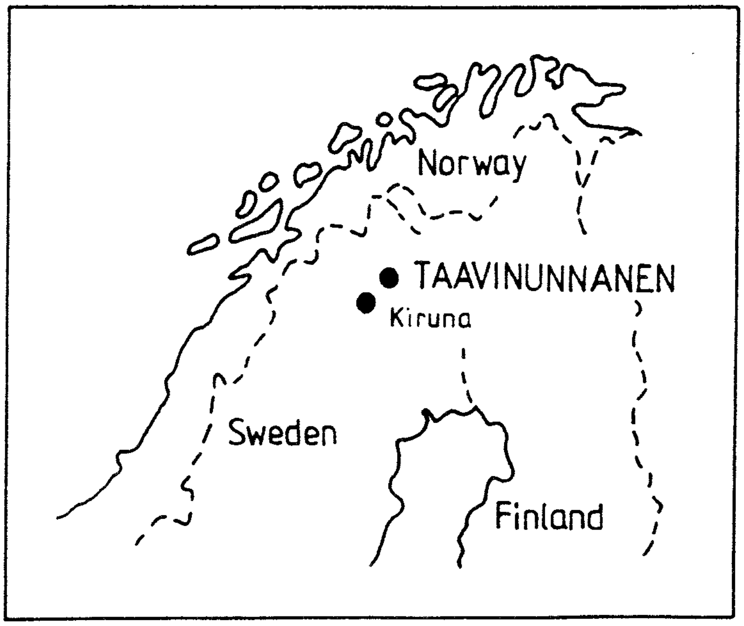

Figure A1. Location of the Taavinunnanen gabbro massif.

1 SELECTION OF THE TAAVINUNNANEN GABBRO

The Taavinunnanen gabbro is one of several large gabbro massifs, >50 km^2, found in the northernmost part of Sweden. Taavinunnanen and three other large gabbro massifs were selected in 1980 because of their large sizes, more or less circular shapes and depths exceeding 1 km, as indicated by magnetic and gravimetric modelling. Petrophysical analyses on outcrop samples indicated homogeneous petrological conditions for three of the selected gabbros. The exception was the Taavinunnanen gabbro that consists of layered gabbro.

During the summer of 1981 field visits were made to all four gabbros. During these visits estimates were made of lineament density, degree of outcrops, homogeneity of the gabbro and frequency of fractures in outcrops. In addition, information regarding non-geological factors, such as accessibility and landownership, were obtained.

The studies resulted in recommending the Taavinunnanen gabbro for drilling. This was mainly based on the low lineament density of this gabbro together with a high degree of outcrops. The latter was regarded important for the geologic modelling, especially since only one borehole was planned for the site. The main negative factor considered for the Taavinunnanen site was the absence of roads and railways. All material for the drilling and other activities therefore had to be transported to the site by helicopter or by snowmobile.

2 SCOPE OF INVESTIGATION

At the time of site selection a modern geological map in the scale of 1:50 000 was available for the Taavinunnanen region (Hallgren, 1979), as well as a relatively comprehensive geophysical material. The latter included magnetic and radiometric maps from low-altitude airborne surveys, and gravimetric maps from ground surveys. There was also an extensive amount of petrophysical data available from studies of outcrop samples (Henkel, 1981).

The PRAV/SKB surface investigations at Taavinunnanen included the following activities:

- lineament interpretation
- geological mapping
- fracture surveys
- chemical analyses of outcrop samples
- microsonde analyses of thin-sections from outcrop samples
- VLF-profile, for borehole location

The borehole investigations included the following:

- drilling a 700 m deep cored borehole (diameter 56 mm, inclination 85°)
- core mapping
- chemical analyses of core samples
- microsonde analyses of thin-sections
- thin-section microscopy and X-ray diffraction analyses of fracture fillings

- natural radiation log
- borehole deviation log
- single point resistance log
- normal (1.6 m) and lateral (1.65 m) resistivity logs
- self potential (SP) log
- temperature log (measured at two different times)
- salinity log

- water injection tests in 25 m sections (26 tests)
- water injection tests in 100 m sections (6 tests)
- water injection tests in 2 m sections (142 tests)
- single packer tests from 630 m and 680 m to the bottom of the borehole

- water sampling in isolated borehole sections at 493 m and 651 m

Summaries and overall evaluation of the Taavinunnanen studies are found in Gentzschein & Tullborg (1985) and in Brotzen (1985).

3 GEOLOGICAL AND GEOPHYSICAL STUDIES

3.1 General

The Taavinunnanen gabbro is located 35 km ENE of Kiruna. The region has a subpolar climate and is used by the laplanders for reindeer breeding. The nearest road is located at 10 km from the site. The Taavinunnanen gabbro is elliptically shaped, 50 km^2 in size, and forms a mountain reaching 250 m above the surrounding valleys. The altitude of the mountain top is 780 m.a.s.l., which at this latitude is above the timber line.

3.2 Regional geological setting

The Proterozoic Taavinunnanen gabbro is included in "the younger series of deep seated rocks" according to Hallgren (1979). This series consists of pegmatite, aplite, granite, perthite-monzonite, syenite, gabbro and anorthosite (Ambros, 1980), and is regarded as the last major plutonic event within the mapped area. A geological map of the Taavinunnanen gabbro and its surroundings is shown in

Figure A2. Components of the series are considered to be approximately 1.5 Ga (Welin, 1970; Gulson, 1972). Older rocks on the map sheet are i.a. quartzites, the Haparanda series (quartz, diorite, granodiorite, monzonite and gabbrodiorite) and metadolerite. Oldest rocks are quartzite, limestone, basalt, tuffite and tuff. A granitic basement has been found.

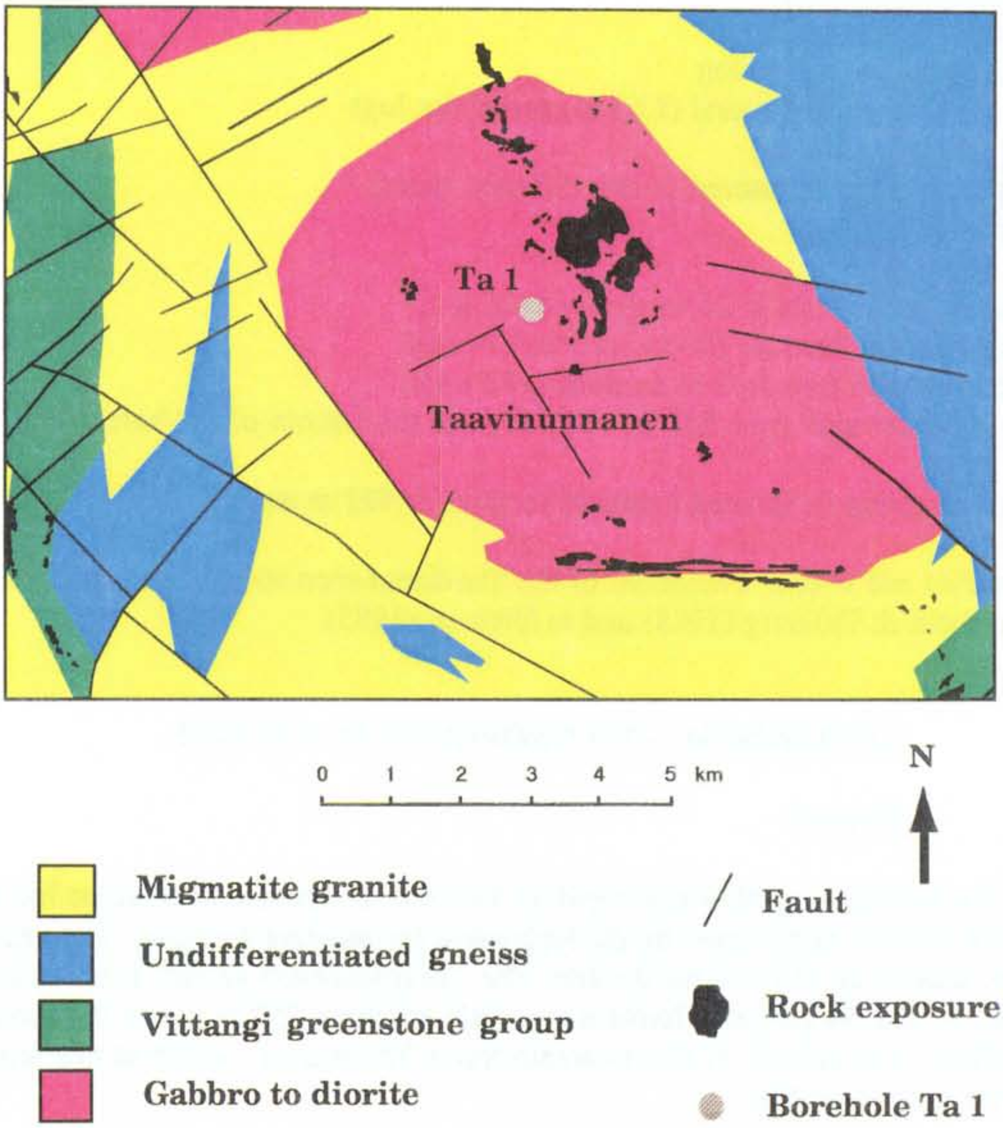

Figure A2. Generalized geological map of the Taavinunnanen gabbro and its surroundings. (After Hallgren, 1979, bedrock map, Soppero SV).

Interpretation of airborne magnetic maps (Henkel, 1981; Ahlbom et al., 1982) shows a dominance of NE to NNE trending regional fracture zones in the region surrounding Taavinunnanen. Old as well as young reactivated fracture zones are recognized. A fault where late Quaternary reactivation has occurred is located just outside the Kärkejaure gabbro massif, approximately 20 km away from Taavinunnanen (Henkel et al., 1983).

No regional fracture zone penetrate neither the Kärkejaure nor the Taavinunnanen gabbro bodies. This has been suggested to be a result of a higher mechanical strength for these bodies, compared to the surrounding bedrock.

3.3 Petrophysical characteristics

The Taavinunnanen gabbro constitutes a well defined magnetic structure in a surrounding of low-magnetic bedrock. The average magnetic anomaly associated with the gabbro is 2000 nT. Susceptibility measurements on outcrop samples show a complex composition of the gabbro. There are samples consisting of only paramagnetic minerals, as well as samples consisting of up to 10 % of magnetite. This variability reflects the strongly layered character of the gabbro. Figure A3 shows an interpretation from the airborne magnetic data in where the layered structure is prominent. The magnetic layers constitute a well defined synform structure with layers dipping gently towards a central part.

The intrusion of the gabbro massif caused a deformation of the surrounding bedrock which can be observed on the magnetic map at distance of up to 3 km from the gabbro.

There is also a well developed gravity anomaly of 22 mgal associated with the gabbro. Density values from outcrop samples vary between 2.93 to 3.34 g/cm^3 because of the heterogeneity of the gabbro. Based on probable distribution of density within the gabbro body a representative density contrast to the surrounding bedrock of 0.37 was suggested by Henkel (1981). Gravimetric modelling resulted in a gabbro thickness of 1.8-2.0 km. In Figure A4 a profile with the magnetic- and gravity fields associated with the Taavinunnanen gabbro are shown. The figure also includes the lateral and vertical extent of the gabbro as suggested by the gravity modelling.

3.4 Petrographical characteristics

Geological mapping and analyses of outcrops and drill cores confirmed the layered structure of the gabbro. The composition of these layers varies from pyroxenitic to gabbroic due to rhythmic layering and to multiple magma intrusions. The thickness of the layers varies from some millimeters to several tens of meters.

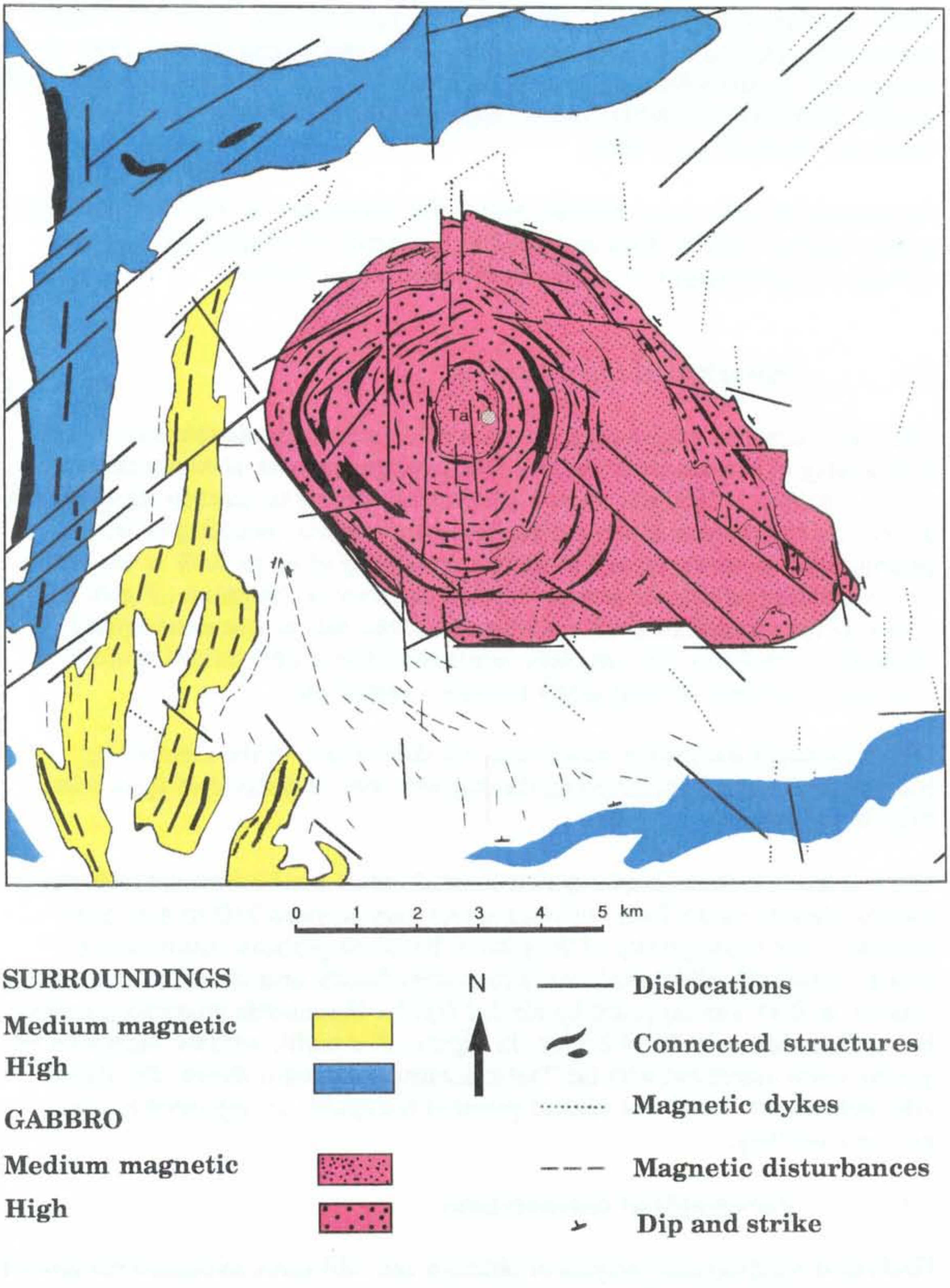

Figure A3. Magnetic structures interpreted from airborne magnetic measurements (after Ahlbom et al., 1982). The location of the borehole (Ta 1) in the stratigraphical center of the gabbro is shown.

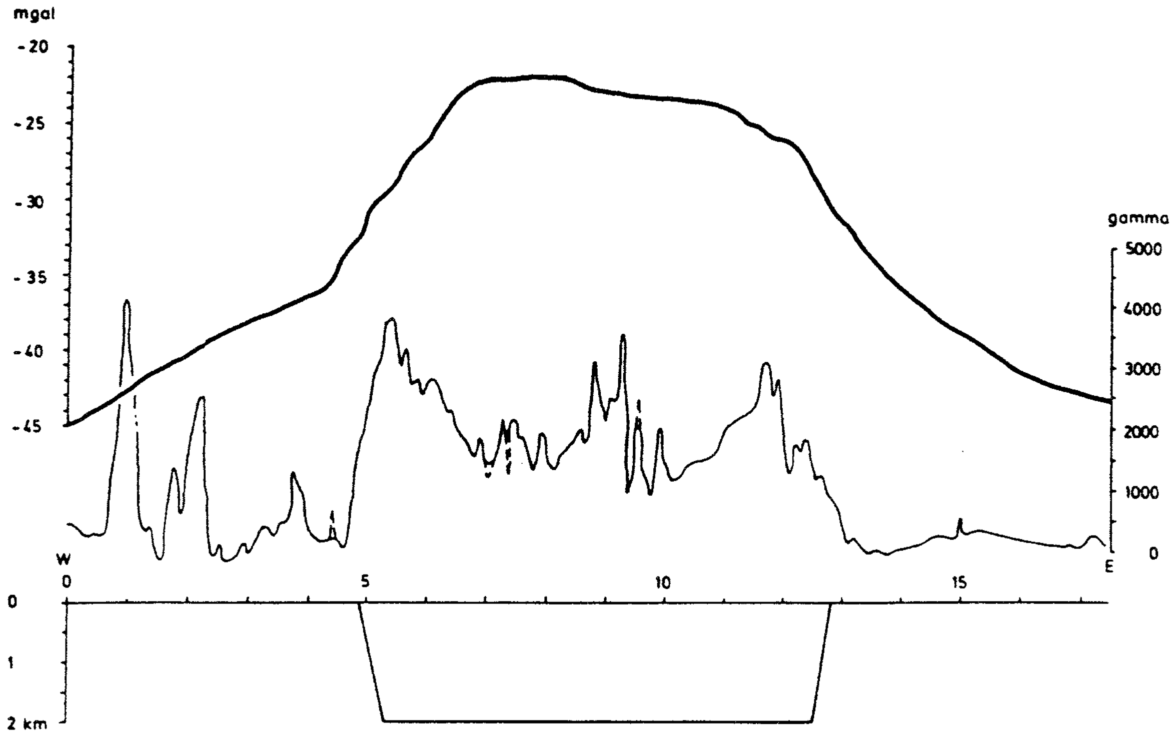

Figure A4. E-W profile showing the magnetic field (thin line) and gravity field (thick line) associated with the Taavinunnanen gabbro. The location and depth of the gabbro, as interpreted on the basis of gravity modelling, is also shown. (after Henkel, 1981).

The dip of layers is 10-40 degrees towards the central part of the gabbro, suggesting a lopolitic shape for the Taavinunnanen gabbro, Figure A5. Geologic modelling, assuming that the gabbro floor follows the dip of the gabbro layers, results in a thickness of the gabbro massif of about 1 km, as compared to the 2 km thickness estimated from the gravity modelling.

The major components of the gabbro are plagioclase (0-75 %), clinopyroxene (0-90 %), olivine (0-30 %) and magnetite (0-20 %). Secondary mineral alteration is found in connection with fractured sections. These sections constitute 14 % of the total core length. Chemical analyses of drill core- and surface samples do not indicate any mineral deposits of economical value.

Steeply dipping aplite and granitic dykes, trending NE-SW with thicknesses of up to 10 m, are observed in outcrops. Based on their occurrence in outcrops they are judged as relatively extensive in length. Some of them probably penetrates the whole gabbro body. Also, one doleritic dyke has been mapped, as well as xenoliths of quartzite. The latter occurrences indicate that the upper part of the gabbro might be close to the original gabbro roof.

Aplite and granite dykes are also found in the drill cores of the Taavinunnanen borehole in where they account for 8 % of the total core length. Some solitary thin basic dikes are also present.

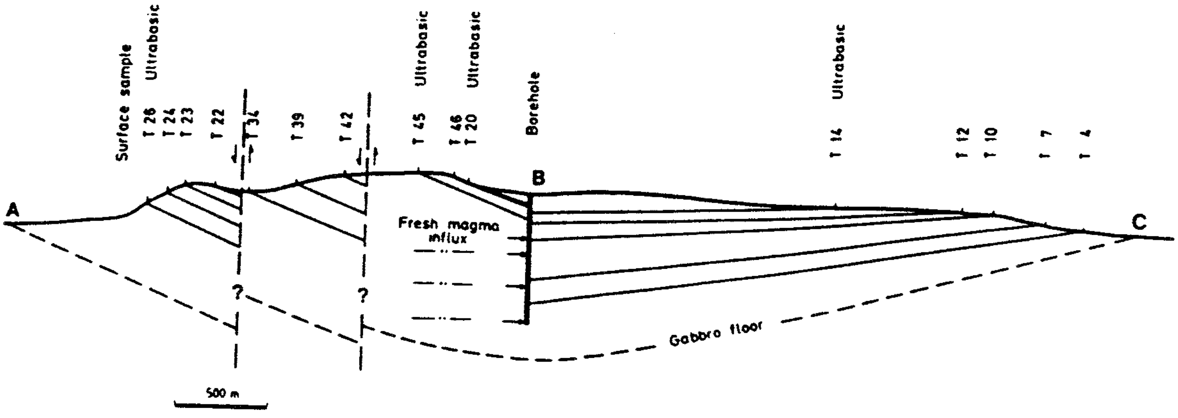

Figure A5. Tentative geological model of the Taavinunnanen gabbro (Larson et al., 1984).

3.5 Fracture zones and fractures

Interpretation of aerial photographs revealed one fracture zone within the gabbro massif which can be related to faulting. Its existence was confirmed by geological mapping which identified mylonites and breccias along the zone. With the exception of this zone, no other fracture zone was interpreted from the aerial photos. This was one of the main reasons for selecting the Taavinunnanen gabbro for drilling.

Fracture zones are however indicated in the aeromagnetic map (Figure A3) and also in the geological cross-section (Figure A2). In the latter case, breaks in petrochemical trends are interpreted as due to faulting. Both the magnetic and the geological indications should however, until confirmed, be regarded as highly uncertain. It has not been possible to trace any fracture zone from the surrounding granites intersecting the gabbro. However, in the surrounding granite, along the southern boundary to the gabbro, strong fracturing have resulted in eroded valleys.

Measurements of fracture orientations in the gabbro outcrops show that short, steep, NE to NNE striking fractures dominate. Some fractures with gentle dips also occur. These are parallel to the igneous layering. Measurements of fractures in the core show a dominance of steep fractures all along the borehole (Larson and Tullborg, 1984). The variation of fracture frequency with depth is shown in Figure A6.

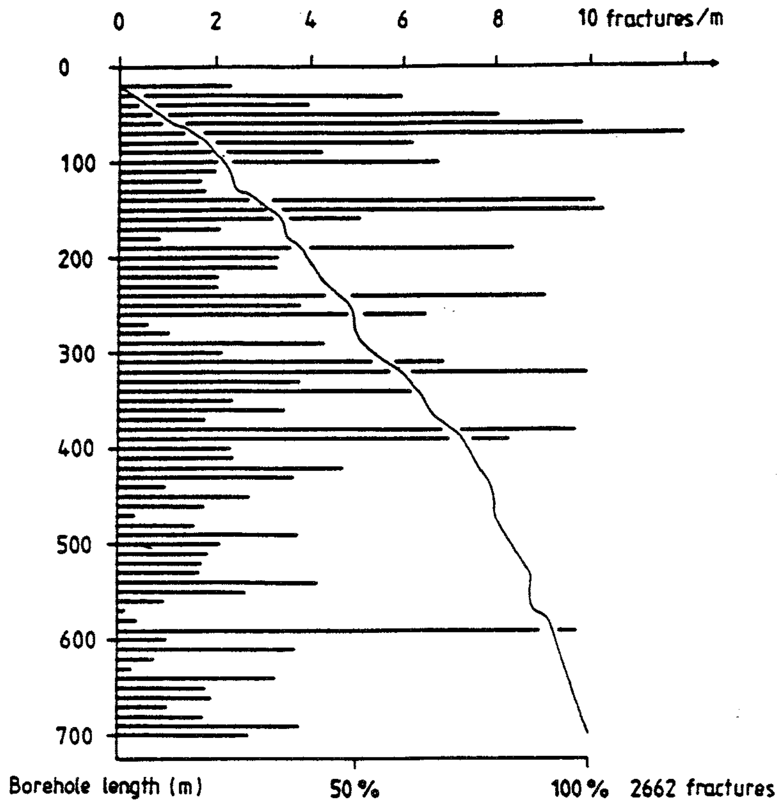

Figure A6. Fracture frequency and cumulative diagram of fractures in the Taavinunnanen borehole.

3.6 Fracture fillings

The dominating fracture fillings in the gabbro are chlorite, calcite and smectite, while chlorite, calcite and quartz are dominating fracture fillings in the granitic dykes (Larson and Tullborg, 1984). Subordinate fracture fillings in gabbro are prehnite and zeolites (stilbite, chabazite and thomsonite). Several generations of calcite are reported. Low-temperature calcite, precipitated by meteoric water, are preferably found within borehole sections with high hydraulic conductivity. Another group of calcite has been deposited by hydrothermal solutions, sometimes together with prehnite.

Oxihydroxides (rust minerals) are commonly found down to a depth of 75 m. The opposite is the case with calcite which is almost lacking in the upper parts of the bedrock, probably due to dissolution by an aggressive water. It is not until 200 m depth before supersaturation in respect of calcite is reached.

4 HYDRAULIC CONDUCTIVITY

The result of water injection tests in 25 m and 100 m sections for the Taavinunnanen borehole is presented in Figure A7. There is a general decrease in hydraulic conductivity in the upper 100-200 m. Below that depth, there is no well defined decreasing trend in hydraulic conductivity. Instead, the general impression below 100 m is low-permeable bedrock, interrupted by highly conductive horizons, spaced some 100 m along the borehole.

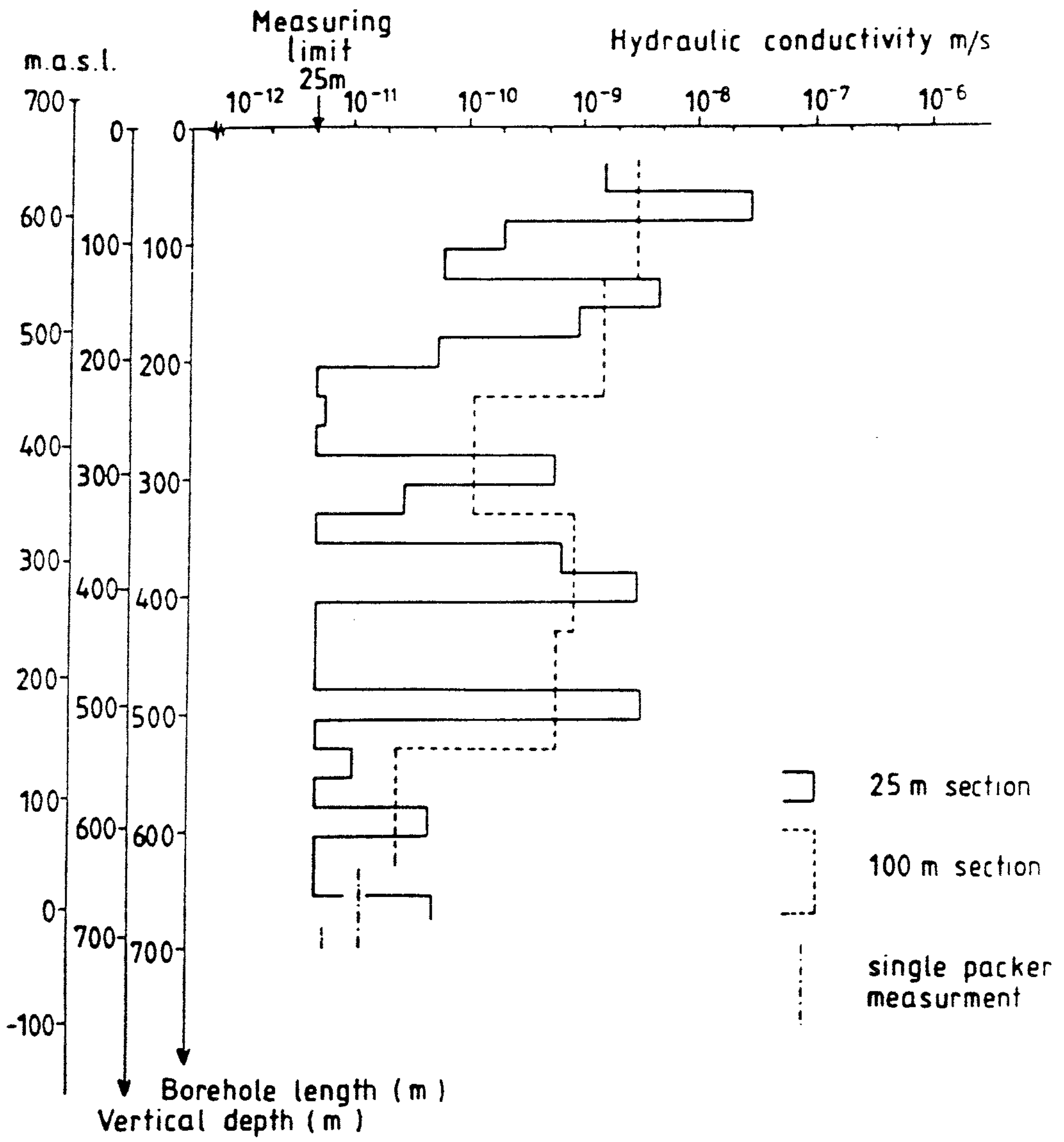

Figure A7. Hydraulic conductivity for the Taavinunnanen borehole. Results from 25 m, 100 m and single packer tests-sections.

This distribution is even more pronounced when considering the 2 m sections, Figure A8. This figure shows the borehole lithological log together with results from the water injection tests from 200 m depth and downwards.

Thin (2-25 m) conductive sections separates large (75-100 m) sections of low conductive bedrock. Observe that all high conductivity values correspond to heterogenous borehole sections, as seen on the lithological log. The most important feature appears to be the granite dykes.

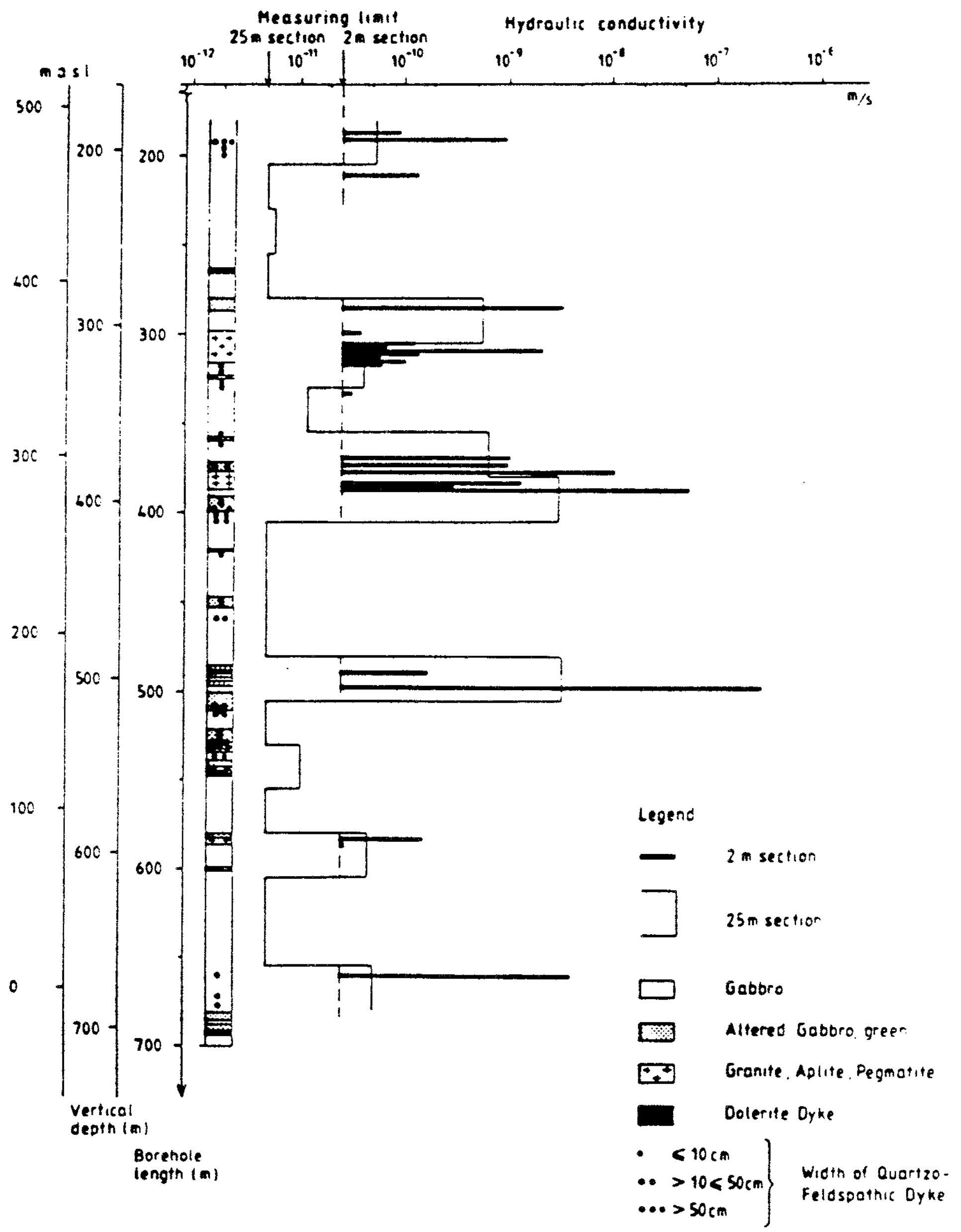

Figure A8. Hydraulic conductivity of the Taavinunnanen borehole from 200 m depth to the borehole bottom. Results from 2 m and 25 m sections are shown together with an lithological log.

To express this result in a more generalized form, the hydraulic conductivity measurements were divided into two data sets, one containing measurements in granite and one representing tests in gabbro (Gentzschein, 1983). A regression curve was fitted to each set of data, assuming that the conductivity, K, varies with depth according to a power function of the form $K(z) = a \cdot z^{-b}$, where a and b are constants and z denotes depth. The resulting curves are presented in Table A1 and in Figure A9.

Table A1. Depth dependence of hydraulic conductivity in gabbro and granite based on results from 25 m water injection tests.

Rock type	Power curve	r^2	n
Gabbro	$K = 4.79 \times 10^{-6} \times Z^{-2.11}$	0.38	27
Granite	$K = 1.86 \times 10^{-6} \times Z^{-1.52}$	0.30	11

Table A1 shows that data are few and that correlation is, in fact, poor. Without attempting any further discussion of the implications of this, it can be seen that the two regression curves in Figure A9 provide a good illustration of the difference in hydraulic conductivity between the gabbro and the granite dykes. At a depth of 500 m, a difference of about one order of magnitude is indicated.

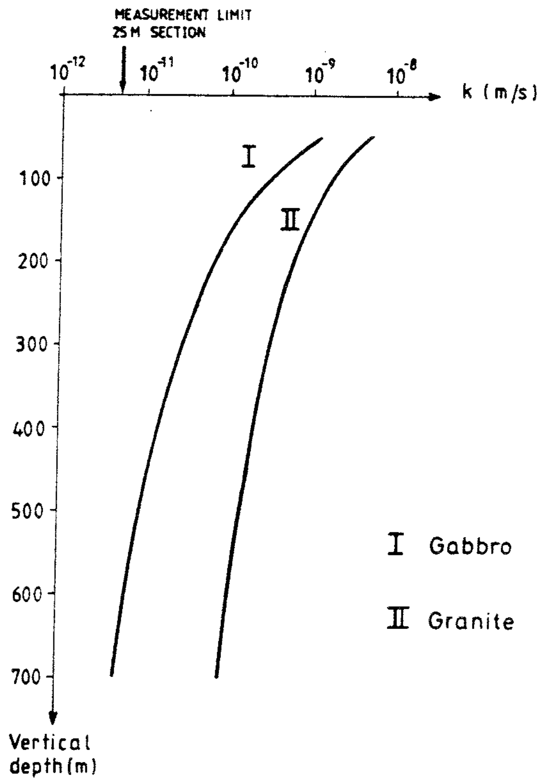

Figure A9. Regression curves for the hydraulic conductivity versus depth for gabbro and granite dykes in the Taavinunnanen borehole (from Gentzschein, 1983).

5 GROUNDWATER CHEMISTRY

Water has been pumped up from two isolated borehole sections in the Taavinunnanen borehole. One section was located at 493 m depth and the other at 651 m. The flushing water used for drilling (taken from a nearby lake) was tagged with sodium iodide to detect any potential contamination in the groundwater samples. The lake water was also analyzed for tritium as a natural tracer control for drilling water contamination.

Analyses of the groundwater samples have been compiled by Laurent (1984) and some field experiments from level 493 m are reported by Smellie (1983). Based on Smellie (op. cit.) a "representative" groundwater sample from level 493 m was selected, together with an estimated suitable sample from level 651 m. (The chemical compositions of these waters are presented in Chapter 6, Table 7).

The water compositions of the samples are far from those expected. The groundwaters (pH 8.8 and 9.6) are very dilute, contain few dissolved ions and correspondingly have low conductivities. A much less oxidising groundwater environment (Eh= -375 mV; O_2= 0 mg/L) is found for the 493 m sample compared to the 651 m level (Eh= +82 mV; O_2=0.6 mg/L). Essentially the two waters can be described as Ca(Na)-SO_4 in type. Another unusual feature is the very high tritium contents, 116 TU and 156 TU respectively. This indicates that the waters are young, i.e. post-1950's, and that these high values (compared with modern-day precipitation in this area of 30-35 TU) are the natural decay residue values from the 1950's when they probably exceeded 2 000 TU.

Contamination by drilling water is considered negligible as indicated by the absence of I^- (consistently <0.01 mg/L) in the selected samples. Furthermore, because of the very high tritium contents in the sampled groundwaters, it is not possible to use the tritium to indicate any surface water contamination because of the much lower amounts present; any near-surface-derived tritium would be effectively masked by the very high levels at depth.

The dilute nature of the groundwaters suggests the mixing of a significant proportion of near-surface-derived water, which would have been initially oxidising. A gradual increase in the reducing character of the groundwater would be expected with increasing depth because of the strong redox capacity of the fracture mineralogy. It is therefore surprising that the sampled horizon at the higher level indicates a more reducing water (493 m; negative Eh and no dissolved O_2) than the lower level (651 m; positive Eh and 0.6 mg/L O_2). In order to explain this apparent anomaly, it is proposed that the groundwater at the upper level is in fact representative of the horizon sampled, and therefore probably typical for the upper 250-500 m of the gabbro. On the other hand, the groundwater sampled at 651 m suggests contamination from a mixture of sources higher up in the borehole (probably pumped around the inflatable packers), in addition to a contribution from the 651 m level.

Accepting that the 493 m level is relatively representative, and that level 531 m is partly contaminated, the fact is that these groundwaters may actually be very dilute. Because they are confined to a restricted number of fracture systems which are highly conductive, residence times are low and rock/water interaction processes are probably not well enough established to impart a greater dissolved ion content to the water. Thus, the main channels for groundwater movement may well be determined by the distribution and intersection network of the granitic dyke occurrences.

List of SKB reports

Annual Reports

1977-78
TR 121
KBS Technical Reports 1 – 120
Summaries
Stockholm, May 1979

1979
TR 79-28
The KBS Annual Report 1979
KBS Technical Reports 79-01 – 79-27
Summaries
Stockholm, March 1980

1980
TR 80-26
The KBS Annual Report 1980
KBS Technical Reports 80-01 – 80-25
Summaries
Stockholm, March 1981

1981
TR 81-17
The KBS Annual Report 1981
KBS Technical Reports 81-01 – 81-16
Summaries
Stockholm, April 1982

1982
TR 82-28
The KBS Annual Report 1982
KBS Technical Reports 82-01 – 82-27
Summaries
Stockholm, July 1983

1983
TR 83-77
The KBS Annual Report 1983
KBS Technical Reports 83-01 – 83-76
Summaries
Stockholm, June 1984

1984
TR 85-01
Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01 – 84-19)
Stockholm, June 1985

1985
TR 85-20
Annual Research and Development Report 1985
Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01 – 85-19)
Stockholm, May 1986

1986
TR 86-31
SKB Annual Report 1986
Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

1987
TR 87-33
SKB Annual Report 1987
Including Summaries of Technical Reports Issued during 1987
Stockholm, May 1988

1988
TR 88-32
SKB Annual Report 1988
Including Summaries of Technical Reports Issued during 1988
Stockholm, May 1989

1989
TR 89-40
SKB Annual Report 1989
Including Summaries of Technical Reports Issued during 1989
Stockholm, May 1990

1990
TR 90-46
SKB Annual Report 1990
Including Summaries of Technical Reports Issued during 1990
Stockholm, May 1991

1991
TR 91-64
SKB Annual Report 1991
Including Summaries of Technical Reports Issued during 1991
Stockholm, April 1992

Technical Reports
List of SKB Technical Reports 1992

TR 92-01
GEOTAB. Overview
Ebbe Eriksson[1], Bertil Johansson[2], Margareta Gerlach[3], Stefan Magnusson[2], Ann-Chatrin Nilsson[4], Stefan Sehlstedt[3], Tomas Stark[1]
[1]SGAB, [2]ERGODATA AB, [3]MRM Konsult AB
[4]KTH
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Sternö study site. Scope of activities and main results
Kaj Ahlbom[1], Jan-Erik Andersson[2], Rune Nordqvist[2], Christer Ljunggren[3], Sven Tirén[2], Clifford Voss[4]
[1]Conterra AB, [2]Geosigma AB, [3]Renco AB,
[4]U.S. Geological Survey
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March 1992

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P J Henderson, J-O Österberg, B Ivarsson
Swedish Institute for Metals Research, Stockholm
March 1992

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Johan Claesson
Department of Building Physics, Lund University, Sweden
February 1992

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Clay Technology AB and Lund University of Technology
December 1991

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April 1992

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Sven Norman
Starprog AB
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Mark Elert[1], Ivars Neretnieks[2], Nils Kjellbert[3], Anders Ström[3]
[1]Kemakta Konsult AB
[2]Royal Institute of Technology
[3]Swedish Nuclear Fuel and Waste Management Co
April 1992

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'Sif Laurent[1], Stefan Magnusson[2], Ann-Chatrin Nilsson[3]
[1]IVL, Stockholm
[2]Ergodata AB, Göteborg
[3]Dept. of Inorg. Chemistry, KTH, Stockholm
April 1992

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Kemakta Consultants Co., Stockholm, Sweden
April 1992

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Sven Norman
Abraxas Konsult
May 1992

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[2]SKB, Stockholm, Sweden
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Scope of activities and main results
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[2] Geosigma AB
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[1]Golder Associates Inc., Seattle, Washington, USA
[2] Golder Associates Geosystem AB, Uppsala, Sweden
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[2] Conterra AB, Gothenburg
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August 1992

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SKB 91
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SKB
May 1992

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September 1992

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Klipperås study site.
Scope of activities and main results
Kaj Ahlbom[1], Jan-Erik Andersson[2], Peter Andersson[2], Tomas Ittner[2], Christer Ljunggren[3], Sven Tirén[2]
[1]Conterra AB
[2]Geosigma AB
[3]Renco AB
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[1]Geological and Environmental Assessments (GEA), Zürich, Switzerland
[2]Geologiska Institutionen, Lund, Sweden
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