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TECHNICAL REPORT 85-57

Hydrogeological and Hydrogeochemical Investigations in Boreholes – Final report

L. Carlsson (Swedish Geological Co, Göteborg)
T. Olsson (Uppsala Geosystem AB, Sweden)

July 1985

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Der vorliegende Bericht betrifft eine Studie, die für das Stripa-Projekt ausgeführt wurde. Die Autoren haben ihre eigenen Ansichten und Schlussfolgerungen dargestellt. Diese müssen nicht unbedingt mit denjenigen des Auftraggebers übereinstimmen.

Le présent rapport a été préparé pour le projet de Stripa. Les opinions et conclusions présentées sont celles des auteurs et ne correspondent pas nécessairement à ceux du client.

This report concerns a study which was conducted for the Stripa Project. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

Das Stripa-Projekt ist ein Projekt der Nuklearagentur der OECD. Unter internationaler Beteiligung werden von 1980-86 Forschungsarbeiten in einem unterirdischen Felslabor in Schweden durchgeführt. Diese sollen die Kenntnisse auf folgenden Gebieten erweitern:
- hydrogeologische und geochemische Messungen in Bohrlöchern
- Ausbreitung des Grundwassers und Transport von Radionukliden durch Klüfte im Gestein
- Verhalten von Materialien, welche zur Verfüllung und Versiegelung von Endlagern eingesetzt werden sollen
- Methoden zur zerstörungsfreien Ortung von Störzonen im Fels

Seitens der Schweiz beteiligt sich die Nagra an diesen Untersuchungen. Die technischen Berichte aus dem Stripa-Projekt erscheinen gleichzeitig in der NTB-Serie der Nagra.

The Stripa Project is organised as an autonomous project of the Nuclear Energy Agency of the OECD. In the period from 1980-86, an international cooperative programme of investigations is being carried out in an underground rock laboratory in Sweden. The aim of the work is to improve our knowledge in the following areas:
- hydrogeological and geochemical measurement methods in boreholes
- flow of groundwater and transport of radionuclides in fissured rock
- behaviour of backfilling and sealing materials in a real geological environment
- non-destructive methods for location of disturbed zones in the rock

Switzerland is represented in the Stripa Project by Nagra and the Stripa Project technical reports appear in the Nagra NTB series.

Le projet Stripa est un projet autonome de l'Agence de l'OCDE pour l'Energie Nucléaire. Il s'agit d'un programme de recherche avec participation internationale, qui sera réalisé entre 1980 et 1986 dans un laboratoire souterrain, en Suède. Le but de ces travaux est d'améliorer et d'étendre les connaissances dans les domaines suivants:
- mesures hydrogéologiques et géochimiques dans les puits de forage
- chimie des eaux souterraines à grande profondeur
- écoulement des eaux souterraines et transport des radionucléides dans les roches fracturées
- comportement des matériaux de colmatage et de scellement des dépôt finals
- méthodes de localisation non destructive des zones de perturbation de la roche

La Suisse est représentée dans le projet Stripa par la Cédra. Les rapports techniques du projet Stripa sont publiés dans la série des rapports techniques de la Cédra (NTB).

ABSTRACT

Underground investigations in boreholes are presumed to be an important investigation technique for the detailed design of a final repository for nuclear waste. The siting of the repository will be based on surface investigations, but for detailed investigations when the access shafts are sunk, investigations in underground boreholes from the initial shafts and tunnels will be of importance. The hydrogeological investigations in boreholes aimed at testing and developing of hydrogeological techniques and instruments for use in an underground environment in order to reflect actual working and testing conditions.

This report is the final report from the hydrogeological investigations in boreholes, and it summarizes the different activities carried out during the course of the program. Most of the included activities are reported in separate internal reports, and therefore only the most important results are included, together with the experiences and conclusions gained during the investigations.

The hydrogeochemical part of the program is in a separate final report, consequently no hydrogeochemical information is in the current report.

RESUME

Les analyses réalisées dans les sondages sont une méthode d'investigation importante en vue de la conception détaillée d'un dépôt final pour déchets radioactifs. La détermination du site de stockage final résultera des études de surface; mais en ce qui concerne les analyses détaillées devant être effectuées une fois les puits foncés, ce sont les investigations réalisées à partir des puits et galeries déjà en place qui seront importantes. Les analyses hydrogéologiques effectuées dans les forages servent au contrôle et au développement de méthodes et appareils hydrogéologiques, dans des conditions proches de la réalité.
Voici donc le rapport final des investigations hydrogéologiques effectuées dans les forages; il récapitule les diverses activités réalisées dans le cadre du programme. La plupart de ces activités ayant été déjà abordées dans des rapports internes séparés, le présent rapport ne mentionne que les résultats les plus importants, ainsi que les expériences et conclusions acquises par les investigations.
La partie hydrogéochimique du programme est résumée dans un rapport final séparé, raison pour laquelle ce rapport ne renferme pas d'informations hydrogéochimiques.

ZUSAMMENFASSUNG

Bohrlochuntersuchungen sind eine wichtige Untersuchungsmethode für die detaillierte Auslegung eines Endlagers für radioaktive Abfälle. Die Bestimmung des Endlagerstandorts wird sich auf oberflächlichen Untersuchungen abstützen, aber für ausführliche Untersuchungen nach dem Abteufen der Schächte werden Untersuchungen in unterirdischen Bohrlöchern von den ursprünglichen Schächten und Stollen aus von Bedeutung sein. Die hydrogeologischen Untersuchungen in Bohrlöchern dienen der Ueberprüfung und Entwicklung von hydrogeologischen Verfahren und Geräten unter realitätsnähen Bedingungen.

Dies ist der Schlussbericht der hydrogeologischen Bohrlochuntersuchungen und fasst die verschiedenen Aktivitäten innerhalb des Programms zusammen. Die meisten dieser Aktivitäten werden in separaten internen Berichten behandelt, deshalb werden nur die wichtigsten Ergebnisse in diesem Bericht erwähnt, zusammen mit den Erfahrungen und Schlussfolgerungen aus den Untersuchungen.

Der hydrogeochemische Teil des Programms wird in einem separaten Schlussbericht zusammengefasst; darum enthält dieser Bericht keine hydrogeochemische Informationen.

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1. INTRODUCTION

1.1 General

The final planning and layout of a deep underground repository for nuclear waste or spent fuel requires detailed information on the geological and hydrogeological conditions at repository depth. For many reasons it appears suitable to aquire this information by subsurface investigations from the access shafts and the repository tunnels as a complement to the surface investigations made for the site exploration. Techniques of underground investigations to collect this information must therefore be developed and tested, and the validity of their results must be demonstrated.

Underground drilling of horizontal or subhorizontal boreholes is a key element for such investigations prior to actual excavation of deposition tunnels, c.f. Figure 1.1. Such boreholes should permit a fairly accurate mapping of rocks, structures and groundwater conditions of the penetrated sections, as well as sampling and testing of the rocks and the local fluids and gases. In addition, the rock volumes surrounding and in between the boreholes may be tested by a variety of geophysical and hydrogeological tools. These technigues and tools should be developed and tested at depths in order to reflect realistic working conditions and pressures. The hydrogeological investigations included in the current report were therefore conducted in the Stripa mine at the depths of 360 and 410 m level. The ideas of underground site investigations were the basic reasons for carrying out the program of hydrogeological investigations in boreholes.

The present report is the final report on the program of hydrogeological investigations in boreholes. A separate final report on the hydrogeochemical part is completed and therefore no hydrogeochemical material is included in this report. During the course of the program a num-

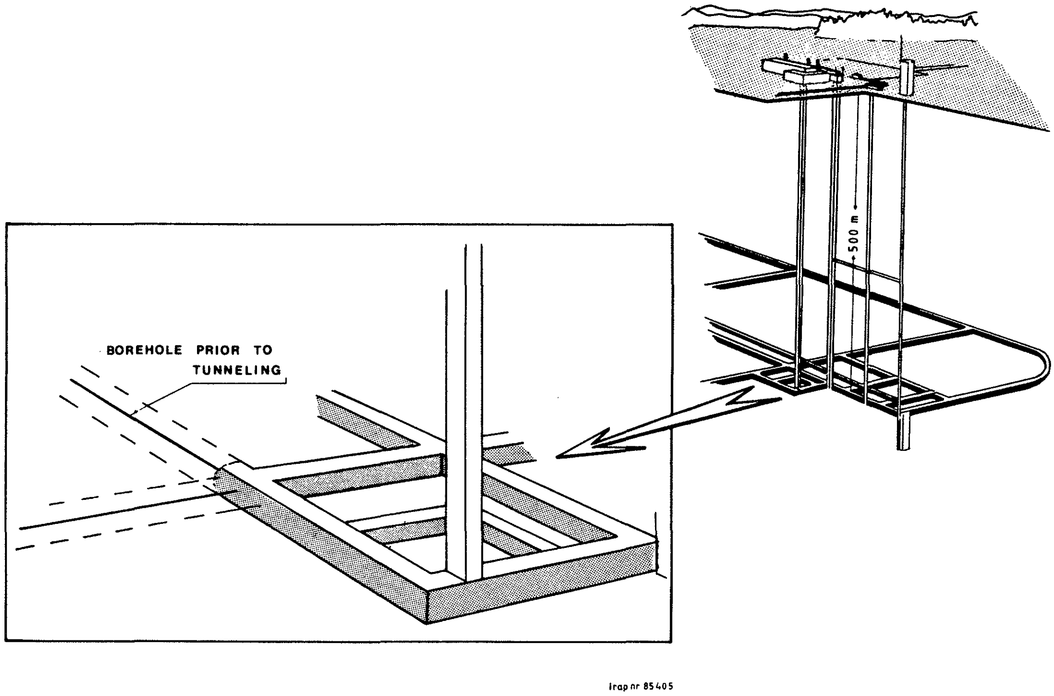

Figure 1.1. Scematic view of subsurface investigations of a repository site. The subsurface investigations take place from the initial shafts and tunnels.

ber of internal reports have been completed and a complete list is included in Appendix 1.

The investigations started in 1980 and the work was carried out in accordance with the defined program (Carlson and Olsson 1981). However, as the investigations continued, minor changes were found to be a necessity in order to adjust the investigation to the actual geological and hydrogeological conditions. The most significant change in the program that took place was related to a heavily fractured zone encountered in the vertical borehole V1. The effect of this zone was that it was not possible to continue the drilling operation without any stabilization efforts. However, stabilization should introduce chemical substances in the rock mass which should affect the hydrogeochemical program. Consequently, borehole V1 was terminated at a depth of 505 m and instead, a new borehole, V2, was drilled at another site in the mine.

1.2. Scope

Hydrogeological investigations in boreholes is one of the programs included in Phase 1 of the Stripa Project. The purposes of the investigations included in the program are as follows:

1. Methodology development for hydrogeological and hydrogeochemical investigations in subsurface nearly horizontal and vertical boreholes.

2. Instrumentation and equipment development in subsurface nearly horizontal and vertical boreholes.

3. Hydraulic, chemical and isotopic characterization of the Stripa granite and groundwaters.

In addition it is also of interest to evaluate the existing drilling technique with small diameters as regards its potential for studies in deep vertical holes as well as in long horizontal boreholes.

The work was mainly carried out in the following four boreholes, c.f. Figure 2.1:

* V1, a 505 m deep vertical borehole
* V2, a 822 m deep vertical borehole
* N1, a 300 m long nearly horizontal borehole
* E1, a 300 m long nearly horizontal borehole

In the vertical boreholes, priority was given to the hydrogeochemical studies and a minor program for the hydraulic testing was carried out.

The aim of the present report is to describe and draw conclusions regarding the different activities included in the program.

1.3 Investigation philosophy

The groundwater system at the Stripa Mine has successively been affected by the mining activities. As the mine was sunk, new flow paths were activated and the drainage thresholds successively lowered. The groundwater system has almost continuously been in balance with the drainage from the underground drifts, i.e. the groundwater system has been in a quasi-steady state condition. In 1976 the mining was terminated, but the drainage pumping continued. After the mining, only minor additional impacts have affected the system. The result is a hydraulic situation which is well suited for hydrogeological studies underground; any controlled disturbance should take place in an affected but steady groundwater system.

A number of techniques may be applied to the underground hydraulic testing. However, requirements and demands from other activities and research programs make some of the probable techniques less suitable. In order to obtain accurate water sampling and analysing results, the groundwater system should be contaminated as little as possible by foreign water and other chemical compounds. This condition calls for a hydraulic testing technique where the groundwater should be extracted rather than injected. Other test programs within the Stripa Project, as for instance, the Buffer Mass Test, was strongly dependent on a undisturbed supply of groundwater and pressure build-up, which calls for a minor extraction and disturbance on the water head around that specific test site.

As the hydraulic testing takes place deep underground, in the potential sink made up by the mine, it was found convenient to utilize the existing potential field for the testing, i.e. to use the natural drainage for water extraction as the main tool and to measure the pressure build-up after shut in or fall-off after release. By this technique, no foreign water is introduced into the groundwater system, and the disturbances on the head should be limited. This technique was used as the main tool both in single hole tests and in interference tests between different boreholes. However, as a test effort water injection tests were carried out in order to test the applicability of these techniques in an underground environment.

2. BACKGROUND

2.1 Test sites

The program for hydrogeological investigations in boreholes was carried out at two specific sites in the Stripa mine. At the SGU-site, which is the main site, three boreholes were drilled, one vertical (V1) and two subhorizontal boreholes (N1 and E1). This site is located at the 360 m mine level. A fourth borehole was drilled from a second site at the 410 m level. This borehole is the old borehole Dbh V1 made during the Swedish-American Cooperative (SAC) program and presently deepened down to a total depth of 822 m (1230 m below ground surface). The locations of the sites and boreholes are shown in Figure 2.1. Data on the boreholes are given in Table 2.1. In addition to these boreholes a number of other holes in the SAC-area were used for minor tests and water sampling.

Table 2.1. Data on the main boreholes included in the hydrogeological program.

BH No	Diameter	Collar coordinates			Length
	mm	X	Y	Z	m
V1	76	336.8	1195.7	356.7	505.9
V2	56	270	1075	407.7	822.0
N1	76	342.2	1194.6	355.5	300
E1	76	338.4	1199.7	355.7	300

2.2 Activities included in the program

The performance of the hydrogeological program required a number of different activities. In the present report the actvities are divided in the following manner:

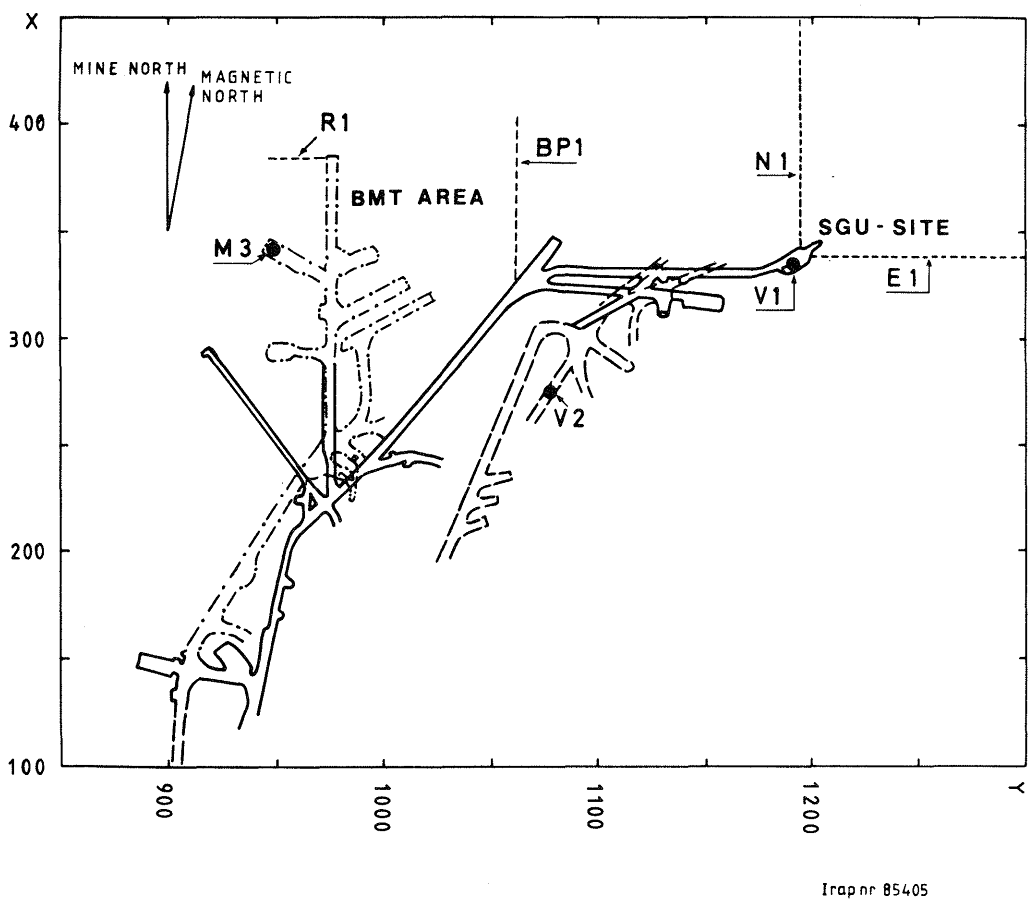

Figure 2.1. Layout of the test site with the boreholes used in the study.

- site preparation (SGU-site)
- drilling
- rock stress measurements
- core logging
- geophysical borehole measurements
- geophysical cross-hole measurements
- core investigations
- hydrogeochemical sampling and analyses
- hydraulic testing, single hole and interference
- modelling

Each of these activities are summarized in the following sections, and the result of each activity is commented upon. Some of the work which was carried out during the course of the program was merely of a surveying character and therefore not suitable to be identified as individual activities. Included in this group is for example the geological characterization and compilation of data on the groundwater head distribution around the mine. The result of this work is included in the general description of the geological and hydrogeological conditions.

2.3 Geological conditions

The target rock for all investigations in the Stripa mine is a rather small intrusive body of granite - the Stripa granite, which is predominantly a grey to reddish, medium-grained granitic rock type of Precambrian age (1690 My). The Stripa granite occurs at the surface in a belt of older supracrustal rocks with structures striking mainly NE-SW. The granite is generally unfoliated, which indicates a relatively mild tectonism after its formation. The largely concordant nature of the granite is not uncommon. Many postorogenetic granites in the Stripa region are mapped as elongated intrusions parallel to the structures of the supracrustal belts (Koark and Lundström 1979).

Leptite, a strongly metamorphosed sedimentary rock, normally of volcanic origin, is the dominant rock type in the supracrustal formation. The iron ore mined at Stripa is associated with the leptite formation. The regional distribution of the different rock types is shown in a broad geological context in Figure 2.2.

The main features of the configuration of the contact between the leptite syncline and the granite are illustrated in Figure 2.3. The contact between the leptite and the granite is transected by the access drift to the SGU-site at 360 m level, approximately 300 m SSE from

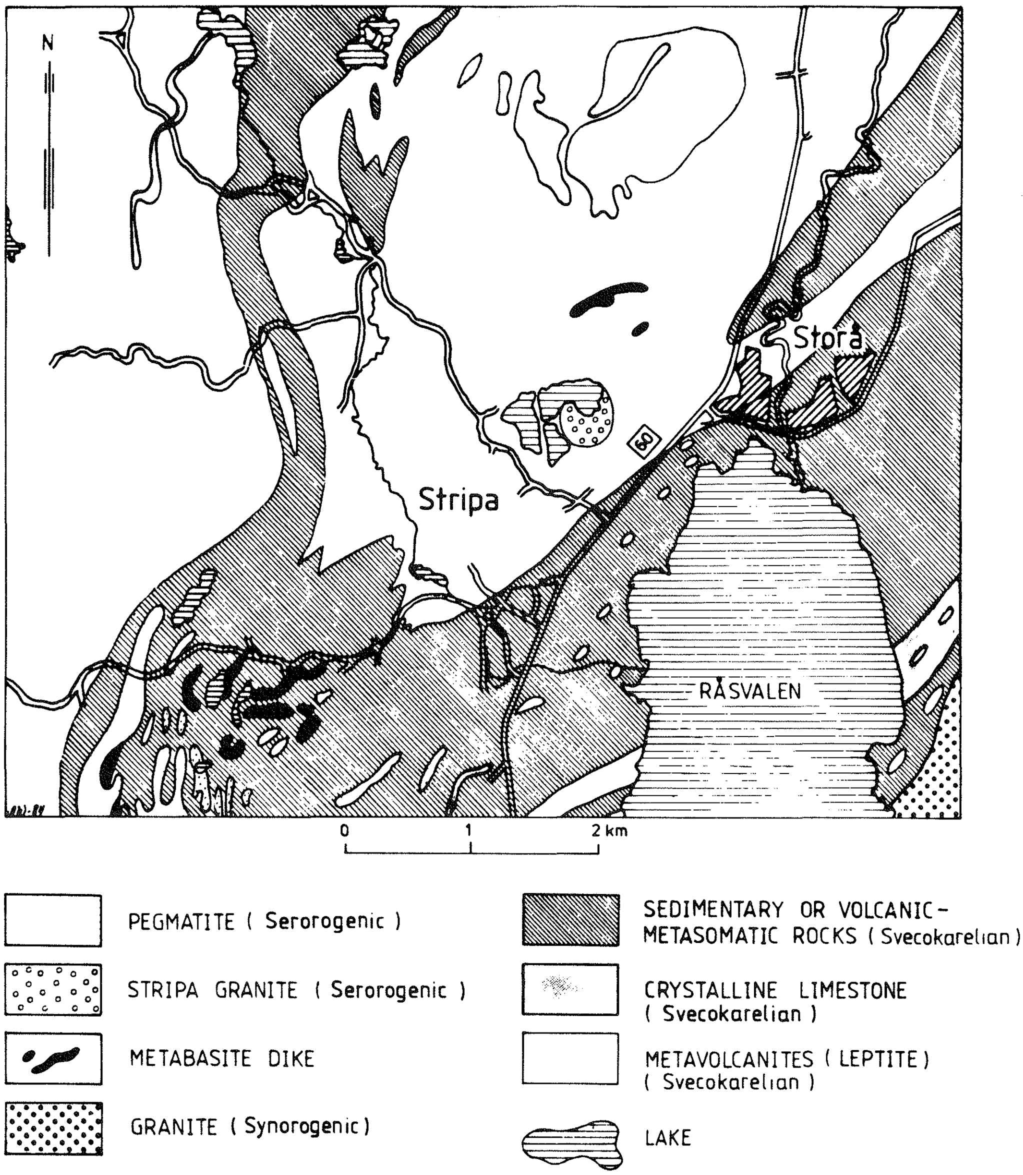

Figure 2.2. Geology of the Stripa area.

the ventilation shaft. The granite at the contact commonly occurs as inclusions or dikes in the leptite.

The granite surrounds the leptites in the Stripa syncline in the north-eastern part of the mine. The limits of the subsurface extension of the granite to SE is partly shown in the vertical section in Figure 2.3. This sec-

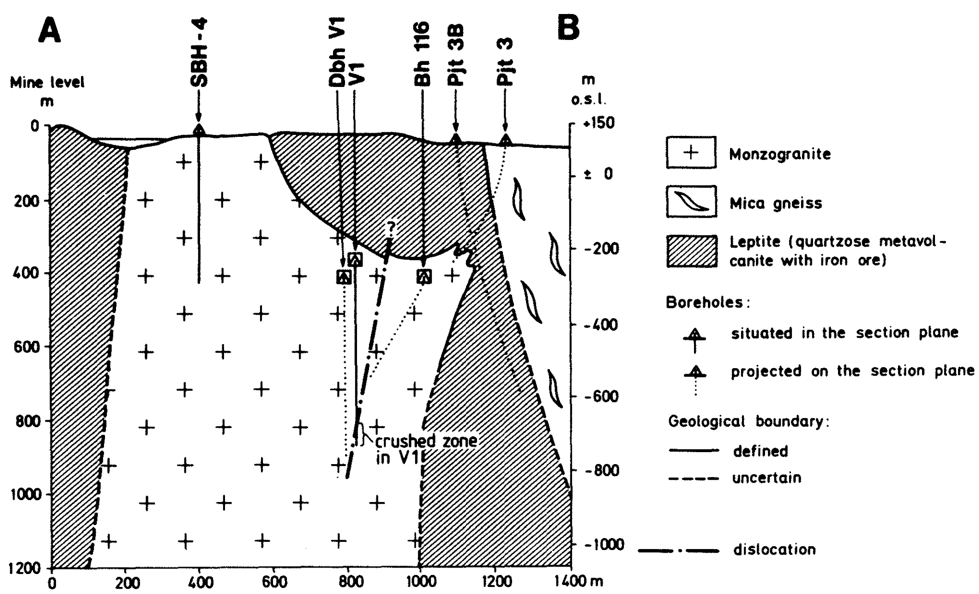

Figure 2.3. Vertical section through the investigation area. The location of the section is shown in Figure 2.4.

tion is taken perpendicular to the contact, i.e. in a NW-SE direction. The location of the section is indicated in Figure 2.4.

The petrology of the Stripa granite was studied by Olkiewicz at al (1978, 1979), Koark and Lundström (1979) and Wollenberg et al (1980). A compilation of available data on geology and petrology of the granite is given by Carlsten (1985). In the different reports the granite is named monzonite or granite which all correspond to the term granite used in the current report.

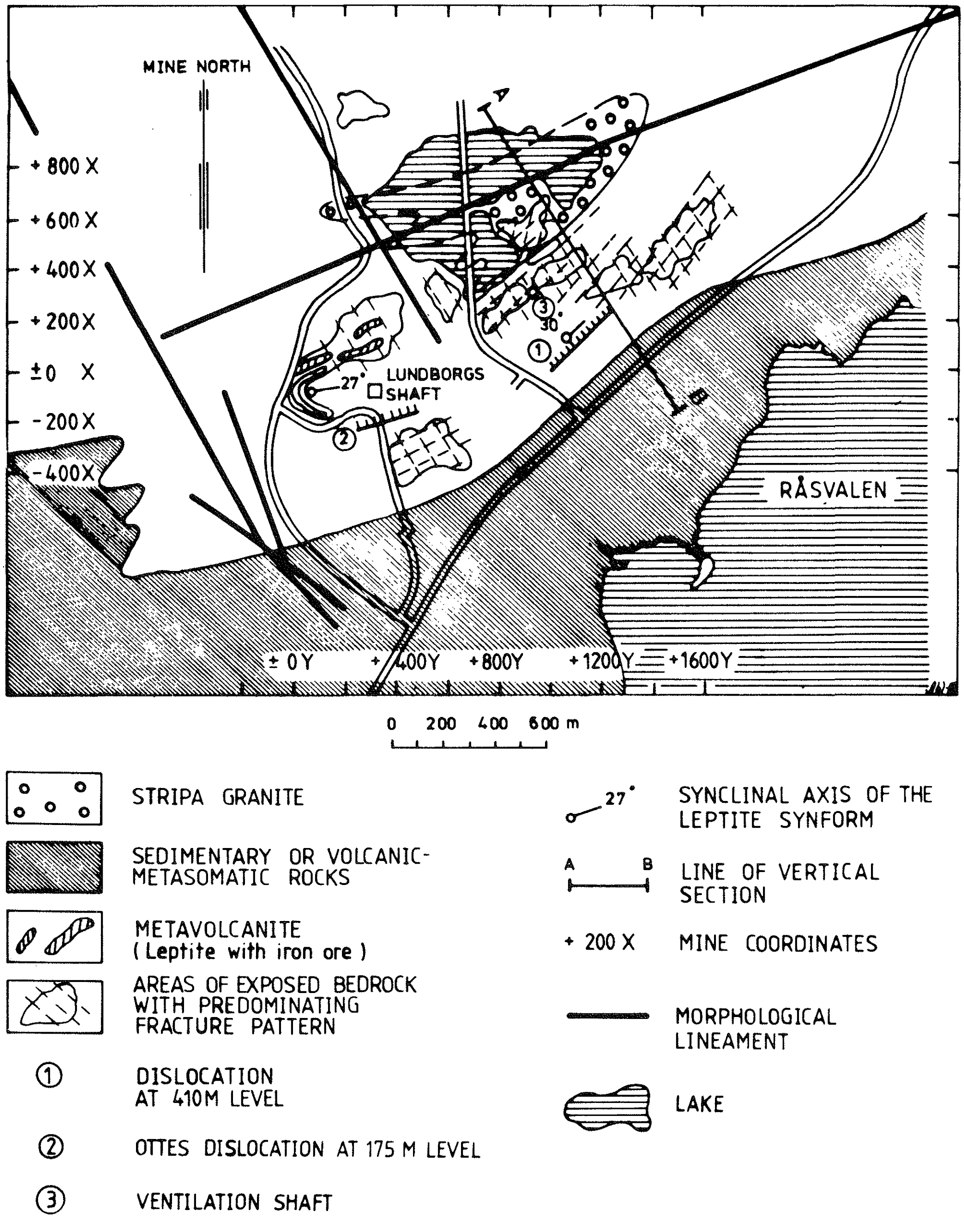

Figure 2.4. Major structures in the Stripa area.

The matrix of the granite consists of approximately 35-45 vol-% of quartz, 35-40 % of partly sericitised plagioclase, 15-20 % of microcline and around 5 % of muscovite and biotite (altered to chlorite). Accessory opaque minerals, garnets and probably zircon also occur (Olkiewicz et al 1979, Wollenberg et al 1980).

A common texture of the Stripa granite of importance for the hydraulic properties of the rock matrix is the abundance of fractures, both continuous and discontinuous on a microscopic scale. Even in relatively unfractured rock samples, fine discontinuous cracks within the primary grains or along grain boundaries are common. These cracks are generally filled with intergrown chlorite and sericite or by quartz and feldspars.

Another distinctive feature of the Stripa granite is the prevalance of cataclastic textures. Rather commonly there is evidence of movements along fracture surfaces or breccia zones or slickensides and fractures filled with a microscopically irresolvable clay-rich falut gouge and closing round fragments of granitic rock (Wollenberg et al 1980).

The leptite is usually a grey, red or grey-green to black, fine-grained foliated metamorphic rock (microschist) commonly cut by white or light green fractures. Mineralogically it is similar to the Stripa granite. Texturally, however, it does not resemble the granite, as it is finer, more evengrained and homogenous.

Lindblom (1984) completed a study of fluid inclusions on both fractured and megascopically unfractured rock samples from V1 and V2, where it was noted a considerable amount of fluid inclusions in the granite. The total volume was determined to about 20 l/m^3 in fractured rock and about 14 l/m^3 in quartz grains.

2.4 Fractures and fracture zones

In Figure 2.4, the major structures in the Stripa area are visualized. The lineaments in the granite have a direction generally parallel to the syncline axis of the supracrustal formation.

Based on both surface boreholes (SBH 1 and SBH 2) and

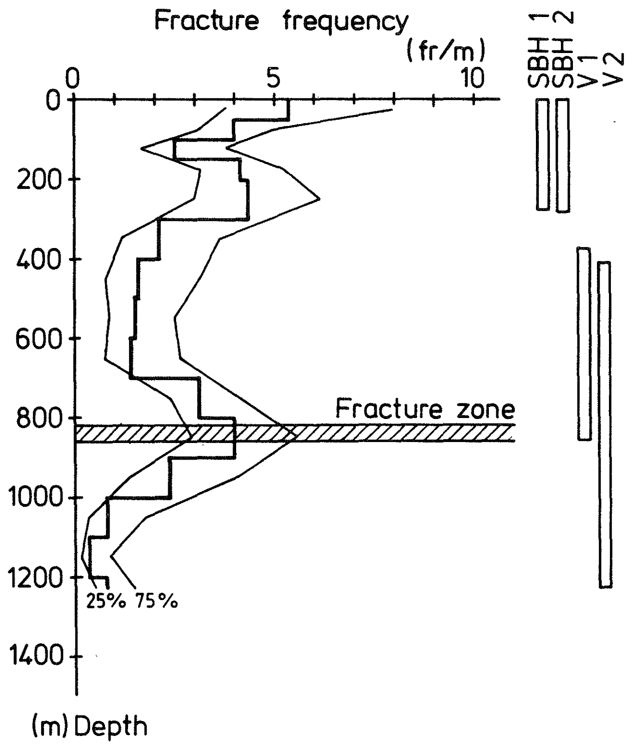

Figure 2.5. Fracture frequency versus depth based on core-logs from SBH1, SBH2, V1 and V2. The frequency is assumed to be log-normally distributed.

subsurface holes (V1 and V2), the variation in frequency versus depth was studied (c.f. Figure 2.5). It must be noted that since V1 and V2 both are vertical, medium-steep and steep fractures will be underestimated. The fracture frequencies obtained in N1 and E1 are also included in the figure. These boreholes are more accurate measures of the steeply dipping fractures at the 360 m level.

A number of zones of fractured or crushed rock exist in the granite. Normally these zones are thin, not exceeding 1 m in the cores, but a few zones are several meters in thickness. A more extensive fracture zone of great hydraulic significance was found in the lowermost part of the borehole V1. In the upper 466 m of the borehole the granite is slightly tectonized, and contains widely spaced fracture zones and crushed zones usually less than 1 m in width. Fracturing tends to be more intense towards the bottom of this section, with a prominent increase in number of subvertical fractures.

A detailed compilation of fracturing of the zone in V1 is impractical for the strongly crushed part of the borehole (466 m down to the bottom at 505 m). In this part as much as 7.7 m of the core is disintegrated or crushed to rubble. The number of fractures in the crushed zone is partly based on an estimation (38 % out of 510 fractures within this 40 m wide zone) and their dipping were not possible to establish. The fracture frequency is 12.9 fr/m in the zone to be compared to 1.5 fr/m for the rock mass above the zone.

The fracture zone in V1 gave a high water inflow. The hydraulic conductivity determined was high in comparison to the rock mass and the zone is of crucial importance for the groundwater occurrence and flow in the granite. However, the extension and orientation may be given different explanations.

Three probable different explanations exist of the geometry of the fracture zone found in V1, none of which is more reliable than the others.

* A zone striking N70E and dipping 60SE

* A zone striking NW-SE steeply dipping to NE

* The major zone is connected to V2 by a number of minor zones as indicated by the geophysical measurements.

The actual interpretation may as well be a combination of any of the mentioned possibilities. This is discussed later on in section 6.

The mean fracture frequencies for the boreholes included in the hydrogeological program are given in Table 2.2.

Table 2.2. Fracture frequency in boreholes V1, V2, N1 and E1.

Borehole	Fracture frequency (fr/m)
V1 (above the crushed zone)	1.5
V1 (crushed zone)	12.9
V2	2.1
N1	1.6
E1	4.7

Figure 2.6 shows a cumulative fracture diagram for V2 with regard to the dipping of the fractures. It is seen that medium steep fractures dominate while steeply dipping fractures have a low frequency. Flat-lying fractures are in an intermediate position. This is in full agreement with the result obtained in V1 (Carlsson et al 1981). It must be noted that vertical boreholes tend to underestimate vertical or steeply dipping fractures while sub-horizontal or flat-lying fractures are recorded with their actual frequency. With this in mind, it is clearly seen from Figure 2.6 that the steeply dipping fractures dominate and the relative frequency of these fractures inceases with depth with a simultaneous dec-

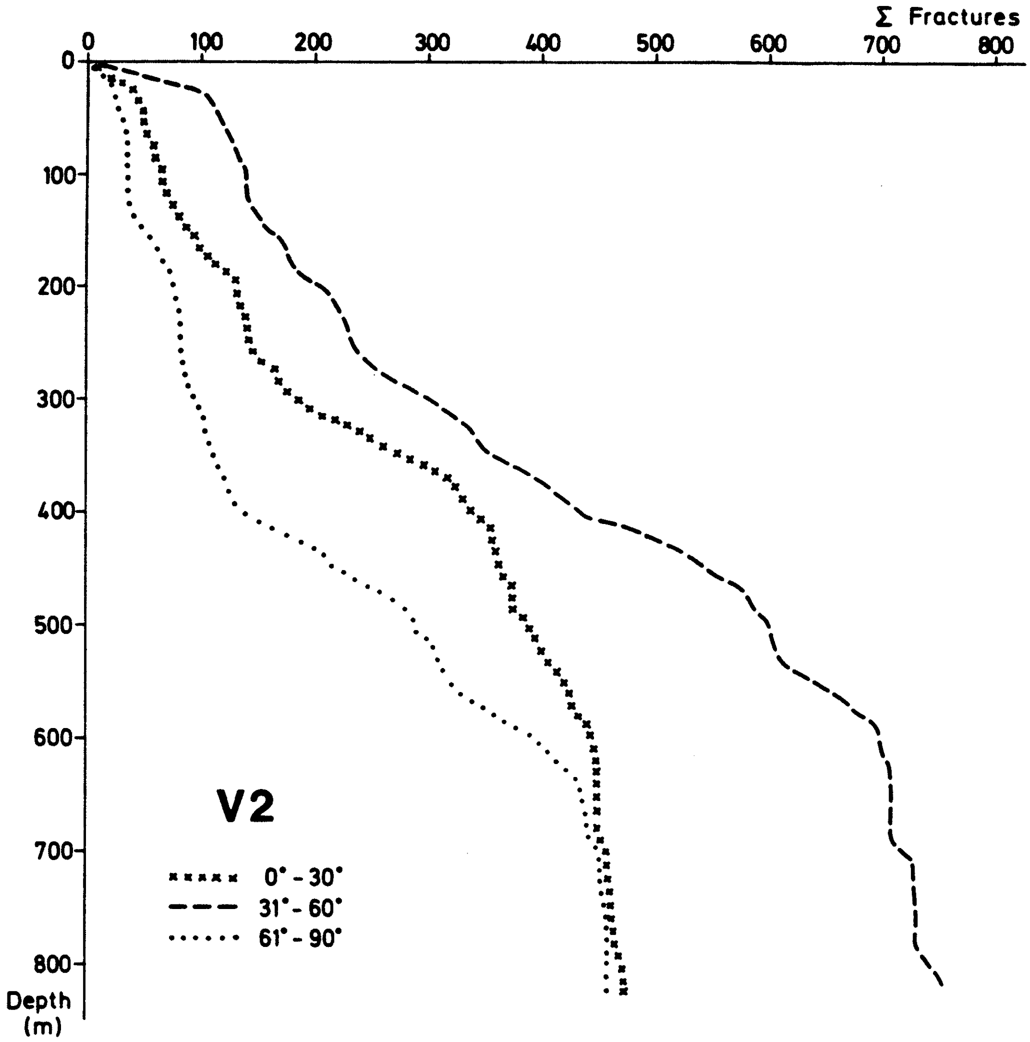

Figure 2.6. Cumulative fracture diagram for borehole V2 with regard to dipping of the recorded fractures.

rease in flat-lying fractures. The flat-lying fractures show a low frequency below approximately 400 m depth with 0.3 fr/m which decreases down to 0.1 fr/m in the lowermost 230 m. This condition indicates that medium steep fractures dominate the fracture system and the horizontal fracturing becomes more sparse at depth.

The fracture pattern which predominates in the rock mass at the SGU-site may be established by the fracture orientation data from the boreholes. Boreholes N1 and E1, which have 100 m of oriented cores each, show a rock mass dominated by steeply dipping fractures in N30E. Other fracture sets of importance are N30W and N10E, both steeply dipping. However, both of these boreholes are nearly horizontal, which indicates that flat-lying fractures will not be penetrated by the boreholes and consequently they will be underestimated. The vertical boreholes may serve as a tool to evaluate the existence of flat lying fractures.

Steep fractures dominate clearly the fracture pattern and make up as much as 40 per cent of all fractures in the rock mass adjacent to the SGU-site. Medium steep fractures makes up 31 per cent and the remaining 20 per cent are attributed to flat-lying fractures. Thus, it was possible to distinguish the following sets of fractures at the SGU-site:

1. N10E;80E
2. N30E;85E
3. N30W;90
4. Sub-horizontal;25

These sets are shown in the semispherical diagram in Figure 2.7.

The obtained orientations from the SGU-area could be compared with the orientations found in the huge stock of fracture data which exists from the SAC-area (Wollenberg et al 1980, Olkiewicz et al 1979). In that area the following fracture sets were found:

1. NNW-SSE;60N
2. NW - SE;85NE
3. N65W;50SW
4. Horizontal

These sets are also included in Figure 2.7. As seen in

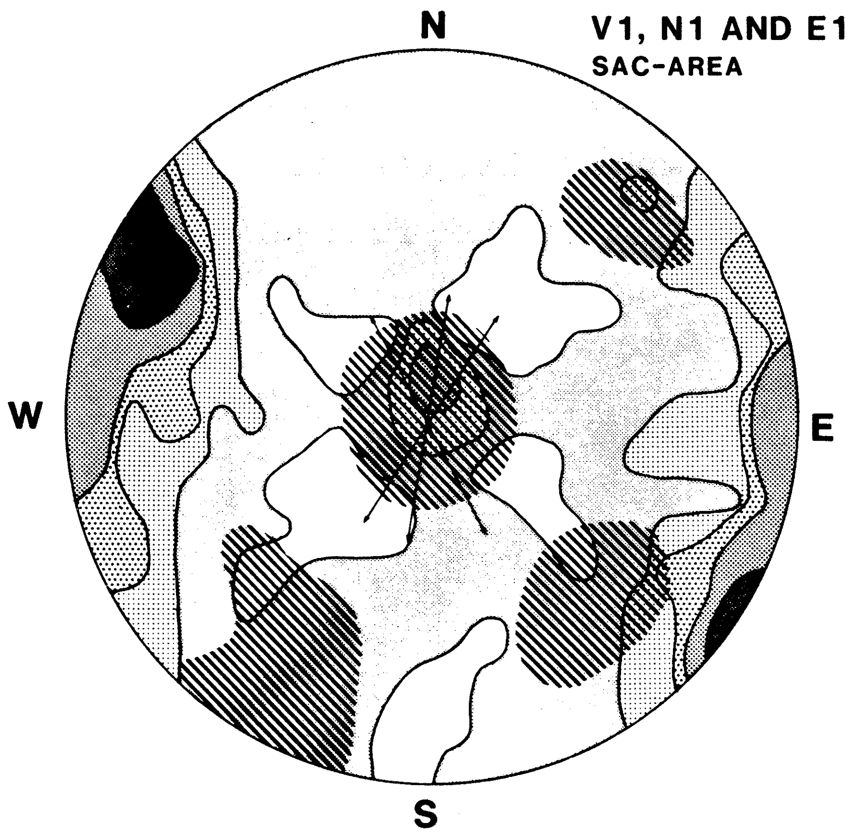

Figure 2.7. Fracture sets obtained at the SGU-site and from the SAC-area (lined parts of the diagram). Semispherical projection, Schmidt net - lower hemisphere.

the figure there is a difference between the fracturing at the SGU-site and at the SAC-area, but some resemblance may be found. The difference may be an effect of the sedimentary structures which could have affected the fracturing of the granite. This is also indicated in Figure 2.4. There seems to be a shift in orientation of the fracture system which probably is governed by the configuration of the leptite syncline. Closer to the contact between granite and leptite, the fracturing is affected by the syncline, while at further distances it seems to be more independent with increased upright and orthogonal fracturing of the granite.

2.5 Hydrogeological conditions

The hydraulic conditions of a crystalline rock mass such as the Stripa granite is mainly characterized by the existing discontinuities which intersect the rock. The granitic rock matrix is from a practical point of view almost impervious and the main flow paths are constituted by the fracture system, zones of fractured or crushed rock and other structural discontinuities. As shown in previous sections, there exists a number of discontinuities, some of which are associated with the syncline structure of the sedimentary sequence and others more independent of it. However, as the dominant tectonization took place before or immediately at the intrusion of the pluton, the granite is intersected only by a few larger fracture zones.

The dominant ruptural deformation is concentrated to the superficial part of the rock, which shows a rather high fracture frequency and a high hydraulic conductivity. This more fractured part of the rock mass extends down to about 250 m depth. Below this level the rock becomes more sparsely fractured, with fractures which are to a great extent sealed. The fracturing continues to decrease and reaches its lowest recorded frequency at the 1100 m level c.f. Figure 2.5.

In the deep-seated rock mass the water flow seems to be channelled in a few zones of fractured rock, where the zone found in the lowermost part of V1 is an extreme example of these flow paths. At these deep levels it is probable that the flow in individual discrete fractures are of minor importance.

The mine itself is one of the most important structures governing the water flow in the area. It acts as a drain, with a drainage threshold which was successively lowered as the mining continued. During the SAC-program measurements were made which illustrated the function of the mine as a draining structure. It is seen from piezometric recordings (Gale 1982) taken at different levels in SBH-1, SBH-2, SBH-3 and DbhV1 (V2) that there exist a well defined gradient towards the excavations.

2.6 Hydraulic head

The hydraulic head in the rock is determined by geological, hydrometeorological and topographical factors. In the current situation it is also to a very high degree dependent on the geometrical configuration of the mine.

The hydrometeorological conditions in the Stripa area can on an annual basis be described by a mean precipitation of 780 mm, an annual evapotranspiration of 480 mm and a run-off of 300 mm (9 l/s sq.km). The climatic conditions are humid and in the run-off term both the recharge and discharge of groundwater, and surface run-off are included.

The geological factor, which determines the hydraulic conductivity and thus, the rate of the groundwater flow in the bedrock points to a rather low conductivity and consequently a low groundwater flow even at high hydraulic gradients. Thus, in combination with the hydrometeorological factor, the conditions are such in the upper part of the bedrock that the groundwater level in general follows the topography.

The piezometry around the mine is complicated due to the inhomogeniety of the area at large. That is, the existence of the ore-body in a deformed surrounding of sedimentary rocks, in combination with the drainage effects due to the mine. However, piezometric recordings exist from the granite area, both from boreholes at the surface and from the underground excavations.

Seven shallow boreholes were drilled at the surface as shown in Figure 2.8, and in addition a number of deeper

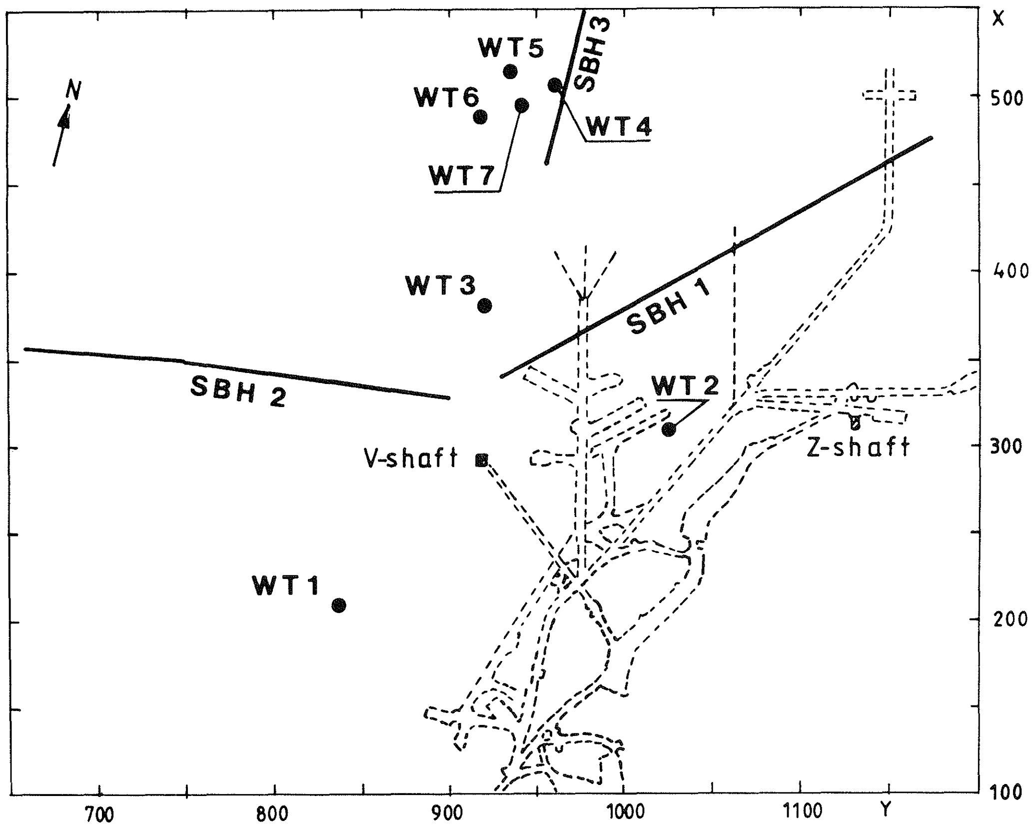

Figure 2.8. Area map of the investigation area with the different boreholes used for piezometric recordings. The WT-series denotes shallow boreholes and SBH-series, deep core-drilled holes. Both series are drilled from the surface.

core-drilling are also included in Figure 2.8. Recordings of the head in these holes provide a basis for the variations in groundwater level and the vertical head distribution. Figure 2.9 compiles the head distribution in some of the deeper boreholes. The groundwater level variations are much more significant than expected in an undisturbed rock mass of this kind. Longer periods of draught result in a continuous lowered level, and no base flow is approached. This is due to the draining

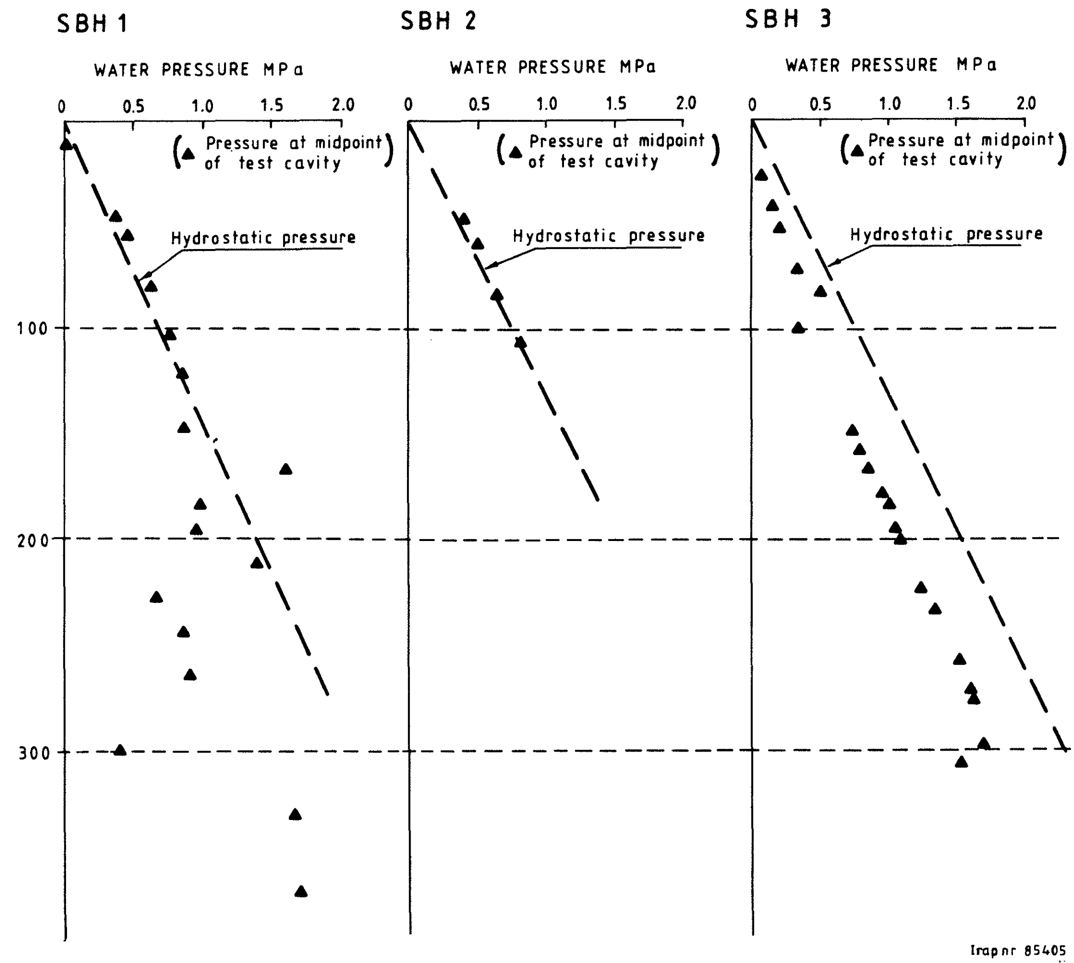

Figure 2.9. Pressure recordings along the deep surface boreholes SBH1, SBH2, and SBH3 (Gale, 1982).

effect of the mine which creates a vertical gradient towards the low pressure sink.

The vertical pressure profiles given in Figure 2.9 also show this vertical gradient. The head distribution diverges from the hydrostatic distribution with increasing depth or decreasing distance from the mine.

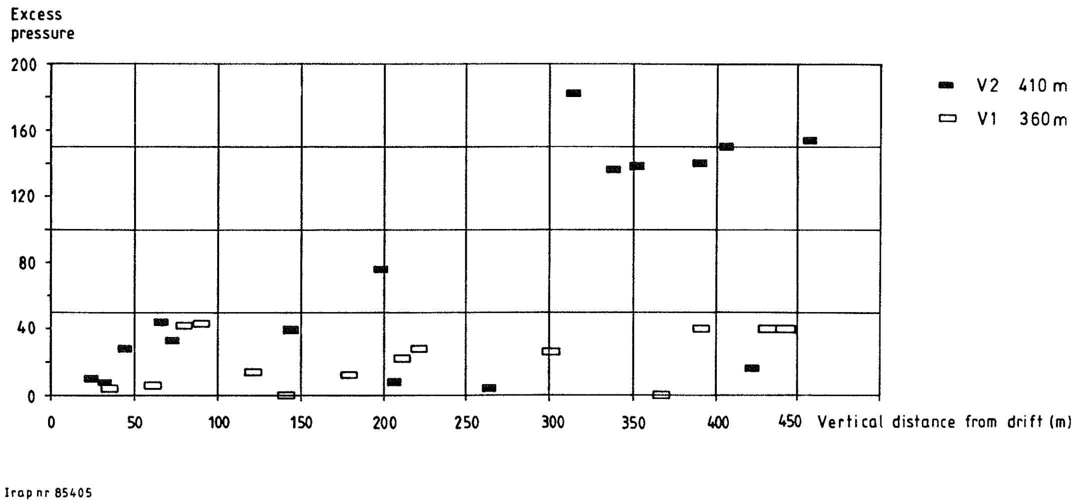

Figure 2.10. Head distribution recorded in boreholes V1 and V2. The head is given in excess head versus the drift.

Also the recordings made within the present program show a considerable impact on the head, as seen in Figure 2.10, where the head distributions in boreholes V1 and V2 are presented. Borehole V1 however, has a slow pressure increase with depth, probably due to the fracture zone found in this borehole. This zone is probably connected to the mine. Borehole V2 shows a much higher groundwater head, however affected by the drainage even at its bottom, i.e. 822 m below the drift, where the head amounts to about 180 m above the 410 m level. This figure should be compared to the virgin head which is estimated to be in the range of 380 m. It should be

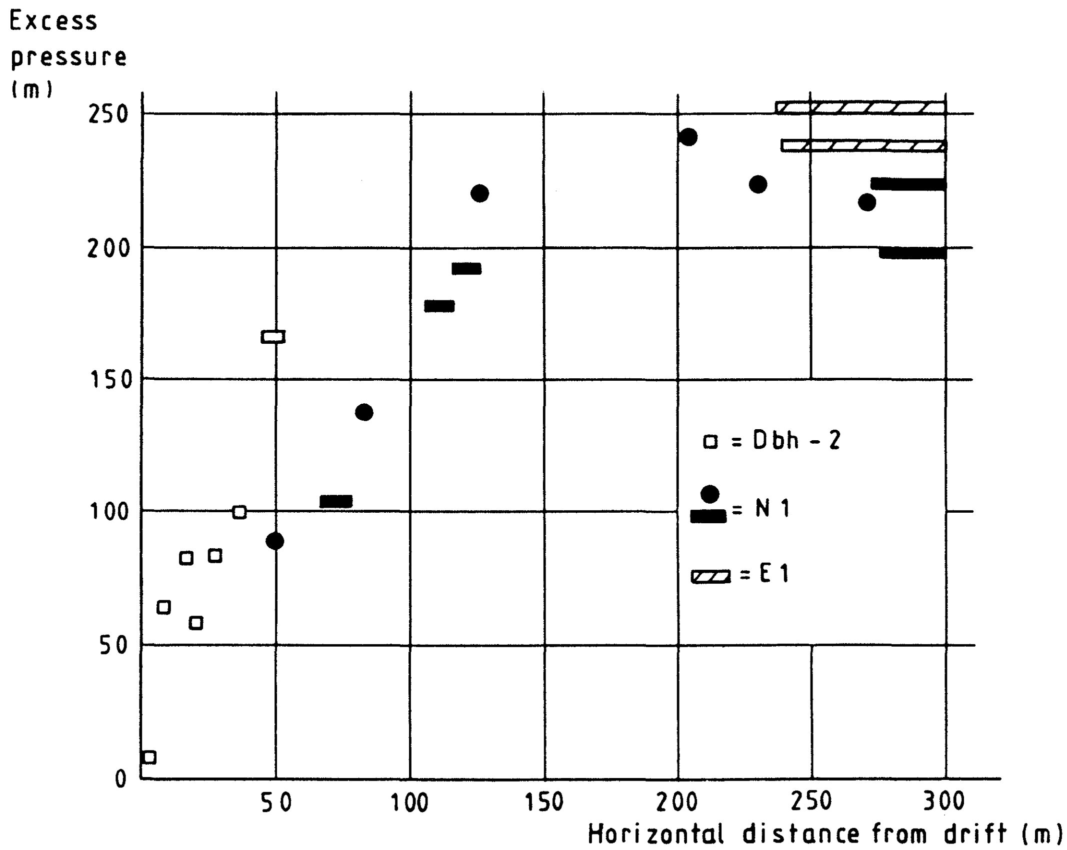

Figure 2.11. Hydraulic head recorded in boreholes E1 and N1 in the present program, and borehole Dbh-2 from the SAC-program. The head is given in excess head versus the drift.

noted that none of these boreholes were in a steady state when the recordings were taken.

The piezometric head in the subhorizontal boreholes E1 and N1 included in the program are presented in Figure 2.11 together with a borehole made during the SAC-period. All these boreholes show a higher head than in the

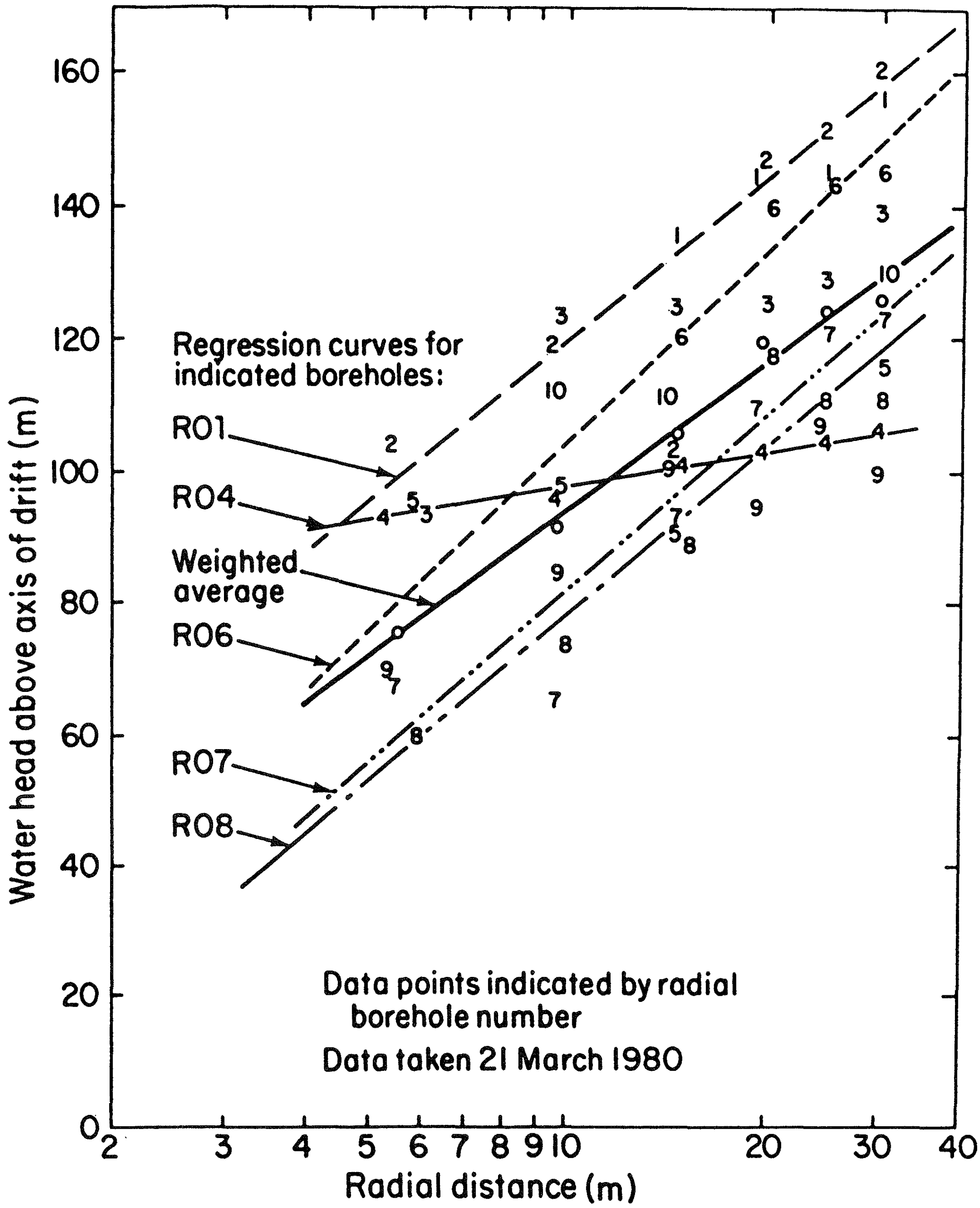

Figure 2.12. Head profiles around the BMT-drift as they were recorded during the macropermeability tests included in the SAC-program (Wilson et al, 1981).

vertical ones. As regards borehole E1 it is seen that a very low head characterizes the outermost 200 m, and it is only in the innermost part that the head reaches the same magnitudes as in N1 and Dbh-2. The reason for this is that E1 is influenced by a drift at the 390 m level which passes some tens of meters from the borehole at a length of 180 m. The head in borehole N1 is affected by a discontinuity in the inner part of the borehole. This zone seems to be in connection with the mine and therefore it acts as a drain of the rock mass.

The recordings made during the SAC-period yield valuable information regarding the near field head distribution around a single drift. The results are shown in Figure 2.12 where the water head versus radial distance is given for the boreholes used for the ventilation test.

The different head recordings mentioned highlight the importance of individual fracture zones, which in the vicinity of an underground excavation act as drains and affect the groundwater head even at great distances. This effect provides that the penetrated fracture zones have a hydraulic connection to the drifts; if not, they will merely acts in a similar manner as the surrounding rock mass. An other effect which is gained from the piezometric recordings is that the impact of the mine is greater in the vertical direction than radially out from the mine. This is also supported by the model calculations made for Stripa (Carlsson et al 1981), the result of which is shown in Figure 9.4 (c.f. Section 9).

Figure 2.13 presents the combined data of deficit in hydraulic head versus the distance to the mine. As can be seen, the mine influences the groundwater head to a distance of 300-400 m in a horizontal direction, and to much greater distance in the vertical direction. The differences obtained in the horizontal direction are due to the existence of minor fracture zones and/or variation in bulk hydraulic conductivity.

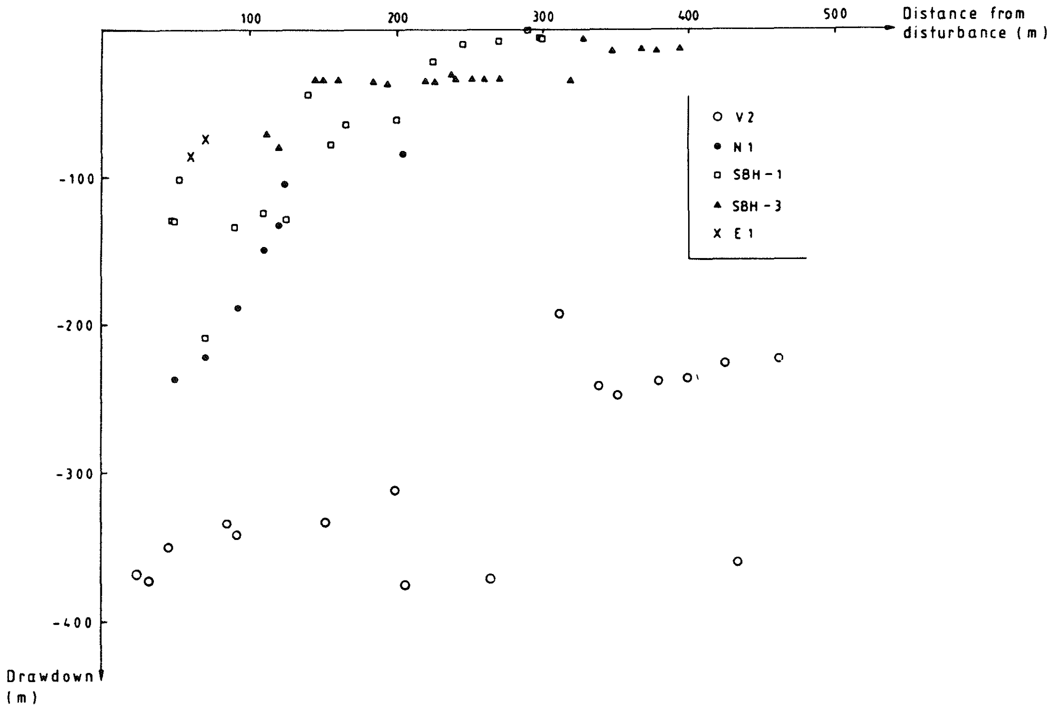

Figure 2.13. Difference in hydraulic head between assumed original hydrostatic pressure and actual recorded pressure in different boreholes versus the distance from the nearest drift.

3. SITE PREPARATION AND DRILLING

3.1. Site preparation

A special site for the hydrogeological investigations was prepared at the 360 m level in the mine. Some specific demands were put on the site selection - water, electricity and compressed air should easily be available, the site preparation should require only minor excavation work, and finally, the site should be located in such a way that the distance to other drifts and planned activities should be as large as possible. The latter was in order to obtain feasible testing conditions and to avoid interference with other activities. After reviewing a number of different possible sites, a site at the very eastern part of the mine was selected, the SGU-site. At this site a minor investigation drift already existed, and only a widening of the drift was required. At the site housing was constructed for the data acquisition system.

3.2. Drilling program

Originally, three boreholes were to be included in the present program, all located at the main test site, the SGU-site. The vertical borehole V1 was aimed at reaching a total depth of 1000 m and the two subhorizontal boreholes, N1 and E1, were each to be drilled 300 m long. However, due to the geological conditions and consideration to other activities it was decided to terminate borehole V1 at a total depth of 505 m and to reach deeper levels in another vertical borehole, V2, which was an already existing borehole made during a previous research phase. This latter borehole was then deepened from 471 m down to a total depth of 822 m. This gave a borehole layout as shown in the site map in Figure 2.1. The collar coordinates of the boreholes are given in Table 2.1.

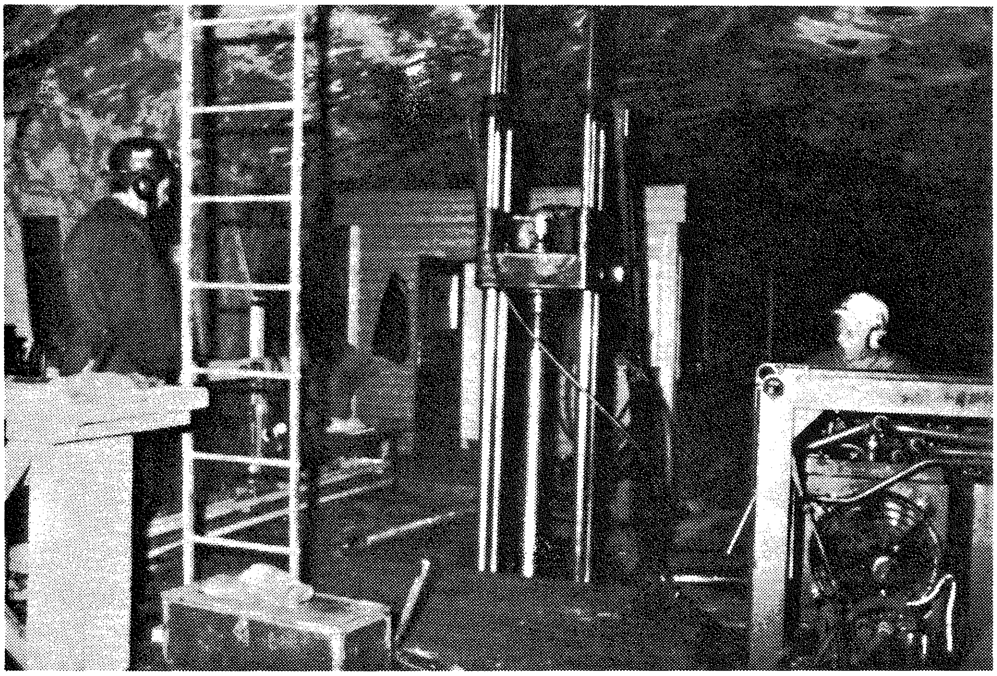

Figure 3.1. Drilling of borehole V1.

The three original boreoles are all 76 mm in diameter while the new borehole V2 is 56 mm in diameter. The drilling procedure is briefly outlined below.

3.3. Drilling technique

All boreholes were carried out as coredrilling, with rotary drilling equipment using standard double core barrels with a maximum uptake of 6 m. The received cores were stored in wooden boxes, each containing 6 m distributed in two 3 m sections. Figure 3.1 shows the drill-rig in operation during drilling of borehole V1.

3.4. Drilling results

In general, the drilling operation was without any significant problems. The drilling rate was mainly affected by the length of the borehole, the deeper the borehole, the longer time for each uptake. One major problem was encountered due to geological factors, and that was a heavily fractured zone in V1 which called for some stabilization efforts in order to avoid getting stuck with the drilling equipment. However, it was not possible to carry out any grouting or other stabilization work without interfering and disturbing the hydrogeochemistry of the deep groundwaters. It was therefore decided to terminate the drilling of V1 and instead, deepen another borehole to almost the same depth as originally planned for V1. The advantage of this change in drilling program was twofold:

1. The new test layout was better suited to the actual geological conditions.

2. The disturbance of the hydrogeochemistry was avoided.

Figure 3.2. gives the average drilling rate for boreholes N1 and E1 as a function of drilling depth. As seen, no significant differences were noticed. The penetration rate was very low for the lowermost, fractured part of V1. The second vertical borehole, V2, had a somewhat higher drilling rate with regard to the depth. This is an effect of the higher penetration rate obtained in the small diameter borehole. The total costs for a small diameter borehole will therefore be smaller than for the greater diameter. Based on the figures of the penetration rate and taking the time for uptake into account, the total cost for a 76 mm borehole will be about 150 per cent of that of a 56 mm borehole. This figure should then be compared to the fact that the investigations in small diameter boreholes calls for especially designed equipment, which normally is not commercially available,

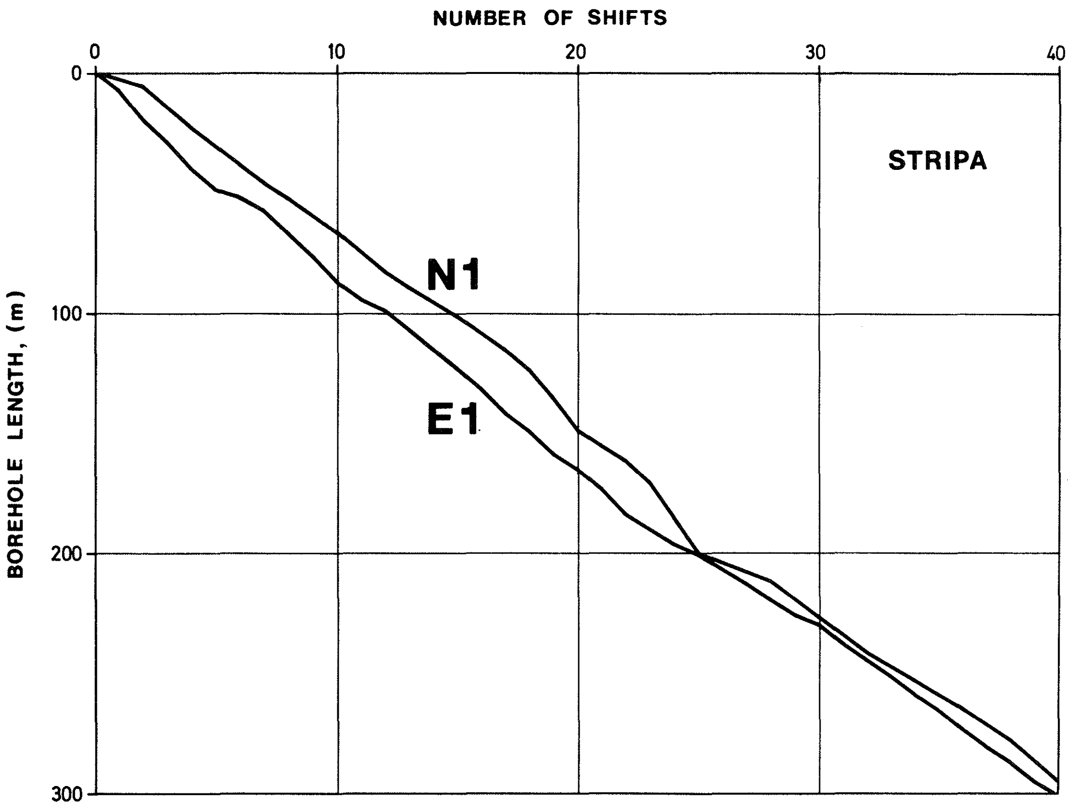

Figure 3.2. Drilling rates for boreholes N1 and E1.

but has to be designed and constructed.

Another factor of importance is the deviation obtained during the drilling. Table 3.2 summarizes the results from the deviation measurements carried out in the present boreholes. With respect to the homogeneity of the Stripa granite only minor deviations were to be expected, especially for the vertical boreholes. A somewhat higher degree of deviation is to be expected in the subhorizontal boreholes due to the forces acting on the drillbits during drilling. The deviation measurements show that the deviation in fact is minor. A comparison

Table 3.2. Results of the deviation measurements in the boreholes N1 and E1. Reflex Fotoborr measuring system. + signs denotes a deviation downwards and to the right.

Borehole	Deviation (m)	
	Vertical	Horizontal
N1	-0.62	+8.90
E1	-1.35	+8.95

between the deviation obtained in the two vertical boreholes shows that there exists no significant difference. A somewhat greater deviation is obtained in the small diameter borehole V2. However, in a more heterogeneous rock mass the difference should probably become greater. This is also the case in a more fractured rock mass.

4. ROCK STRESS MEASUREMENTS

4.1. Measurements performed

According to the defined program, rock stress measurements were to be carried out each 150 m in the vertical borehole, i.e. at 150 m, 300 m and 450 m drilling length with the final depth reached in borehole V1. However, the poor rock quality at the lower part of V1 made any measurement at about 450 m impossible. Thus, the measurements performed include those at 150 m and 300 m, with 4 measuring points at each level. The resuslt from the measurements are presented by Strindell and Andersson (1981).

4.2. Measuring technique

The technique used is a 3-D technique based on the wellknown method of Leeman and Hayes (1966), but developed further by the Swedish State Power Board in order to perform measurements in deep water-filled boreholes. The method is described in detail by Hiltscher et al (1979).

Three strain-gauge rosettes, arranged as shown in Figure 4.1 are cemented to the wall of a small diameter borehole at the bottom of the borehole with its larger diameter (c.f. Figure 4.2). The triaxial stress tensor can then be determined from measurements of the nine single gauges during unloading of the gauges by overcoring with the diamond bit used to drill the larger borehole.

This method was chosen because its theoretical principles are exact and contain only minor approximations (the rock is assumed to be isotropic), the evaluation formulae are simple and the influence of the material constant are easy to assess. In addition, it is the only existing 3-D method for use in deep water-filled boreholes.

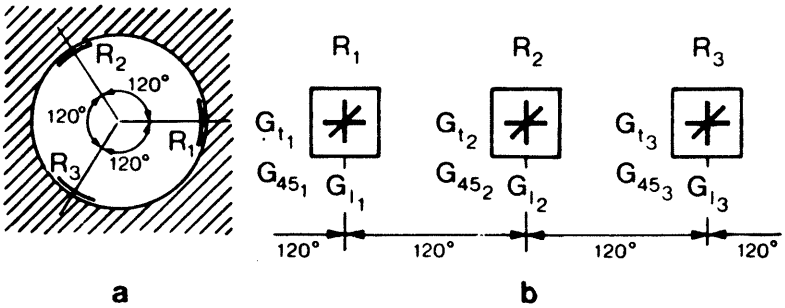

Figure 4.1. Arrangment of the strain gauge rosettes.

Figure 4.2 shows schematically the course of the measurement procedure.

Before the results of a measurement were accepted, tests were made to ascertain that the prerequisities for a correct measurement were fulfilled. Strain gauges glued in a moist environment or under water should be regarded with a certain suspicion. If the gauges show a large amount of creep after relaxation, intruding water is normally the cause and the measurement will be unreliable.

4.3. Results

Youngs modulus and Poissons ratio of the overcored tabular cores were determined through calibration on three cores from each measured level. In this case both the

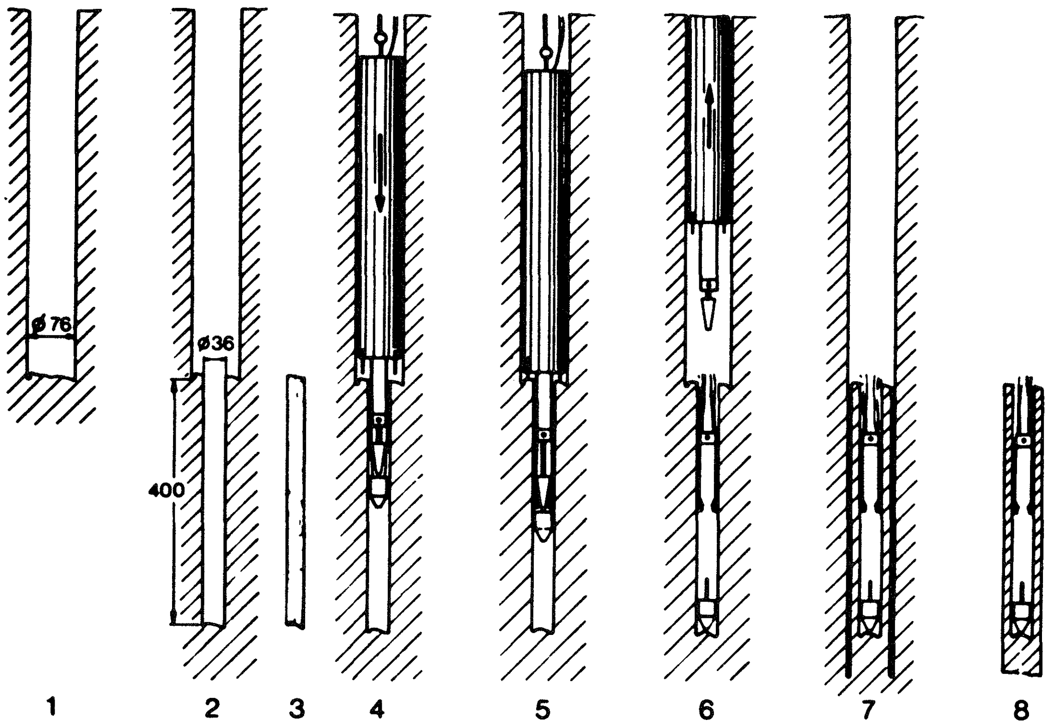

Figure 4.2. Operations for cementing and measuring. The steps in the procedure are given in Strindell and Andersson (1981).

axially and the transversally modulus were determined in order to verify the assumption of isotropy. On the six samples, Youngs modulus varies in the range 58-68 GPa and Poissons ratio 0.16-0.21.

The rock stress distribution was calculated out of the strain values measured on the strain gauges. Figure 4.3 shows the principal stresses and their elevation angles

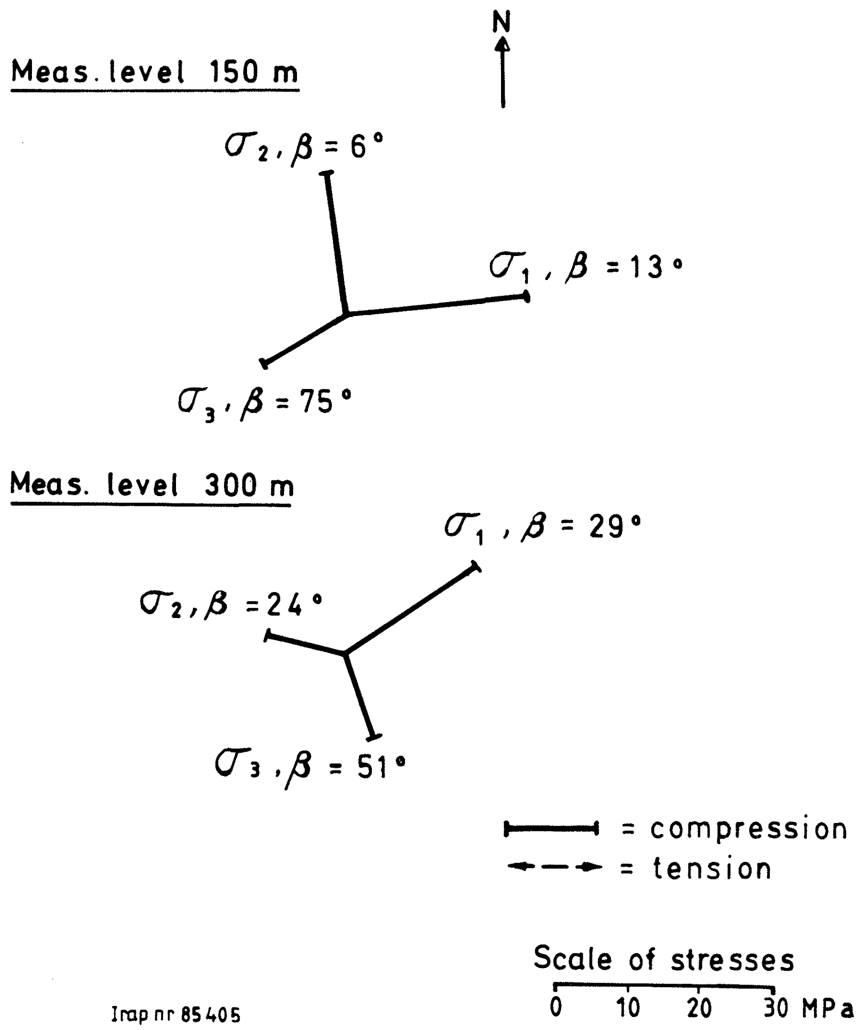

Figure 4.3. Pricipal stresses obtained in borehole V1. The stresses at each measuring point are given with their inclination in relation to the horizontal.

from the horizontal plane and Figure 4.4 shows the magnitude of the principal stresses as a function of the depth. As can be seen, the average stresses at the 300 m level are somewhat higher than those of the 150 m level. The directions of the principal stresses are given in the semispherical diagram in Figure 4.5 in relation to the fracture system at the test site.

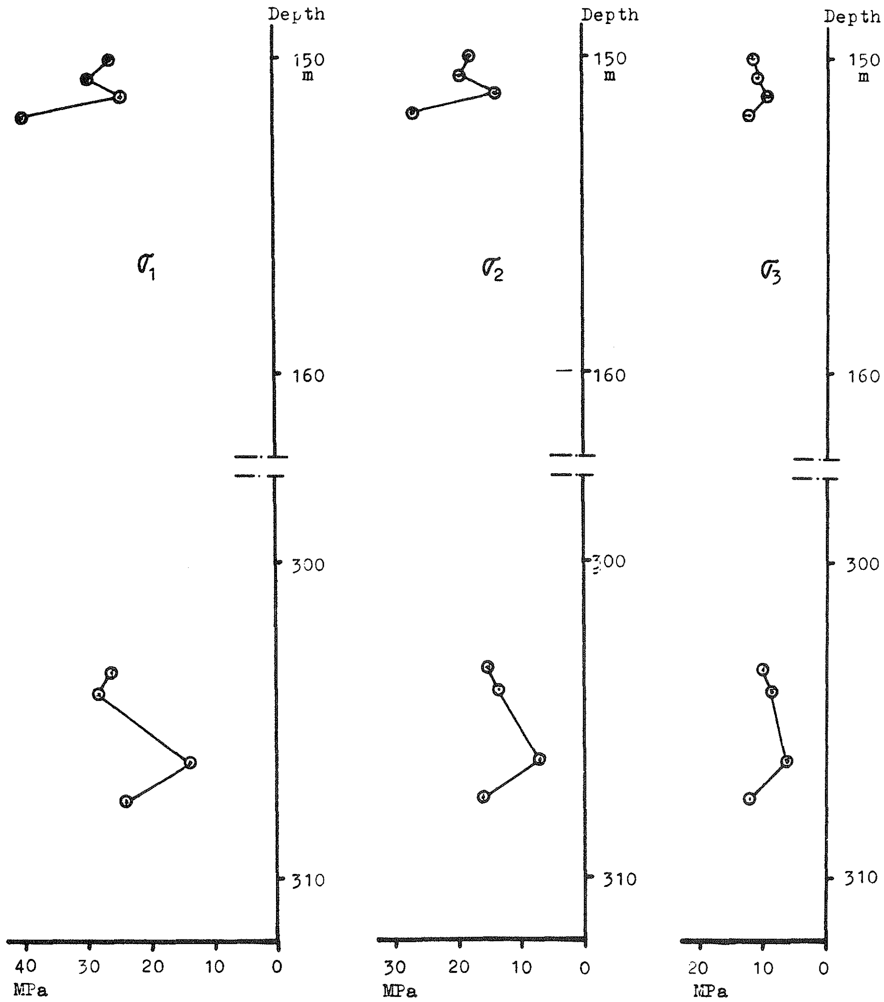

Figure 4.4. Principal stresses in borehole V1 in relation to depth.

In summary, the major principal stress at the 150 m level amounts to about 25 MPa and has an average direction of about E-W. The corresponding values at the 300 m level are 20 MPa and NW-SE. The measured values of the vertical component correspond fairly well to the weight of the overburden.

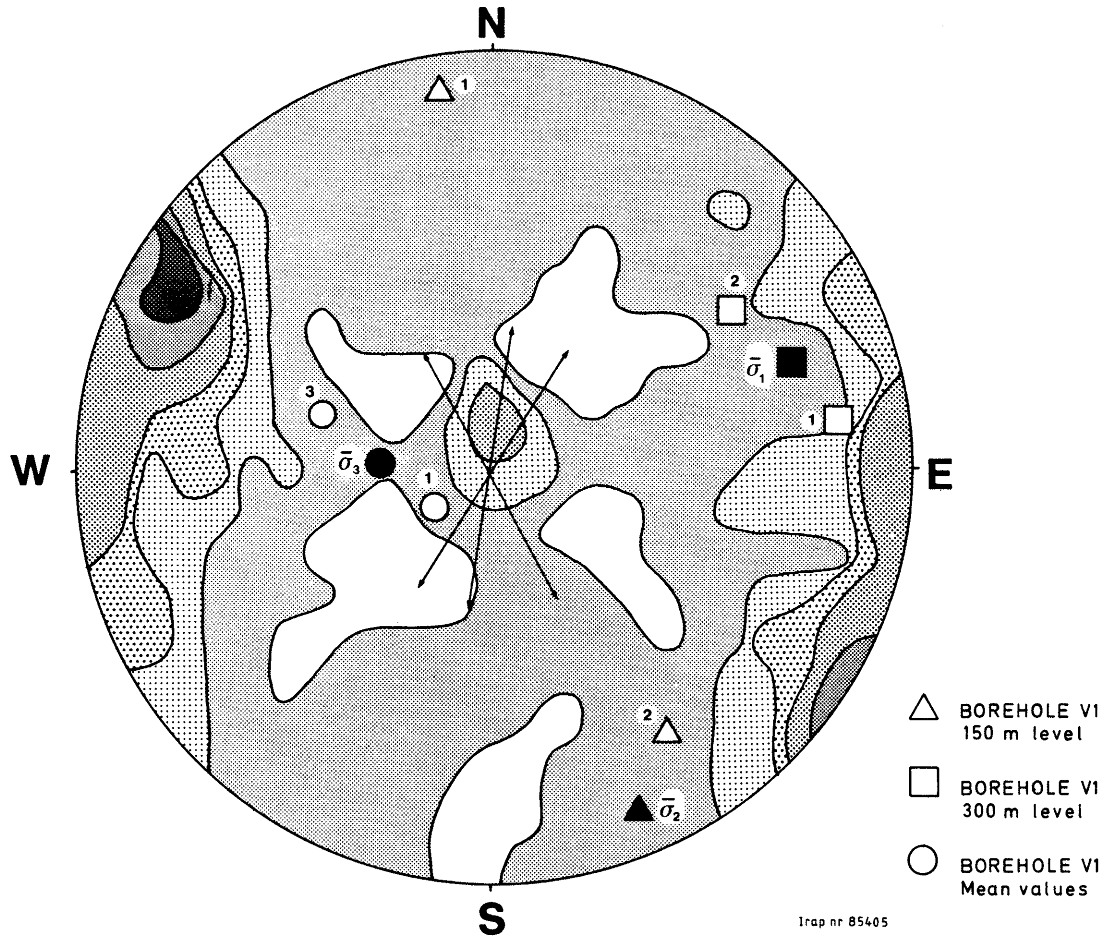

Figure 4.5. Semispherical projection of the axes of the principal stresses in relation to the fracture pattern at the SGU-site.

This rock stress distribution indicates from a hydraulic point of view that the more or less horizontal fractures are attributed to the least closure pressure and those in a N-S to NW-SE-erly direction to the highest closure pressure. Provided that the fracture characteristics are isotropic, the nearly horizontal fractures should have a somewhat higher hydraulic conductivity compared to other fracture sets.

5. CORE-LOGGING

5.1. Core-logging procedure

The cores recovered during the drilling were continuously logged and documented. In total,1928 m of core were logged. The diameter and the core length from each borehole is given in Table 5.1.

Table 5.1. Core lengths and diameters of the different boreholes.

Borehole No	Diameter mm	Core length m
E1	53	300
N1	53	300
V1	53	506
V2	33	822

The cores were stored in wooden boxes, each containing 6 m (53 mm) and 10 m (33 mm) core. During the logging procedure the cores were kept in the boxes. Generally, the logging was made as soon as possible after each uptake. This procedure made it possible to carry out the logging down at the test site, before the core boxes were transported to storage facilities at the surface. The advantage of this was that the cores were logged before any additional transportation damage, and that the logging staff could be in close contact with the drilling staff in order to obtain additional information.

5.2. Logged parameters

The procedure for logging the cores included recordings of distinctive changes in rock type, colour, grain size and characteristics of the fractures intersecting the core. An attempt was made to retrieve oriented cores in the subhorizontal boreholes N1 and E1. This was performed by the use of a heavy iron rod which made a mark on each starting end of the core before drilling. This technique, however, only permitted orientation of about 100 m in each borehole and could only be used in inclined boreholes.

Measurements of the orientation of discontinuities were recorded in relation to the core axis. Afterwards these directions were converted to true directions through the oriented part of the cores. Mapped characteristics were listed in tabular form and contained the following data:

- Coordinate and type of fracture

- Orientation with respect to the core axis

- Mineralogy of infilling material and coating minerals

- Orientation of planar and linear features

- Occurrence of weathering and dislocations

Parallel to the tabular fracture log a detailed graphic log was established in order to vizualize the core. The results of the core logging are presented in different reports (Carlsson et al 1981, Carlsson et al 1982a, Carlsson et al 1982b).

5.3. Results

The results from the core logging are included in the previous section dealing with geology and fracture characteristics (Section 2.3 and 2.4). Most of the information gained is compiled in these sections, but in addition, the results were used for the planning and interpretation of the hydraulic testing and of the hydrogeochemistry.

The parameters logged and the procedure used were the same as are conventionally used in most core-logging programs. This gives a large body of information of which only some are valuable for hydrogeological purposes. However, it was not recognized in the current program that any of the parameters logged could be excluded. Instead a more detailed logging is recomended on the fracture filling material. This will be useful when evaluating the fracture history and tectonism within a potential repository area.

6. GEOPHYSICAL BOREHOLE MEASUREMENTS

6.1 Borehole logging

A geophysical borehole logging program was set up and carried out as a part of the overall investigation program. The aim was to obtain useful data for the hydrogeological evaluation. The logs were intended to:

- locate and characterize fractured zones
- define sections of interest for hydraulic testing
- generally describe the borehole lithology
- obtain variations of the groundwaters in temperature and salinity.

Normally, no single log will give the required information and therefore an integrated logging program is necessary. This will also minimize errors in interpretation and the recorded rock properties are deduced with a higher degree of reliability. In order to obtain the optimal information level, the following logs were used:

- borehole deviation
- gamma log
- point resistance
- resistivity log with normal and lateral configuration
- self-potential log
- temperature and fluid resistivity

The different logs and their capabilities are described in detail by Olsson and Jämtlid (1984).

In order to calibrate the logging results, the physical properties of the bedrock were determined on core samples from N1 and V1. In this respect the following properties were of interest:

- resistivity
- porosity

- density
- induced potential

The results of the laboratory tests are summarized in Table 6.1.

Table 6.1. Mean values of the physical properties obtained from laboratory measurements on core samples (granite) from boreholes N1 and V1.

Borehole	Resistivity kohm	Porosity %	Density kg/m^3	IP %
N1	51.2	0.45	2648	1.79
V1	29.3	0.49	2647	1.41

By the logging program a number of minor fracture zones were identified, some of which were in agreement with the results from the corelogging procedure. Also other information of importance was obtained, i.e. salinity variations, water yielding fractures, and radiation level. Below are the results summarized for each of the logged boreholes. The results of the deviation measurements are included in section 3, Drilling.

<u>Borehole E1</u>. Eight minor fracture zones were located, mainly by the resistivity logs, however none of these zones are indicated as being significantly water yielding. The salinity log gave a fairly constant salinity, between 135 ppm and 160 ppm. The ventilation in the mine has cooled down the surrounding rock mass, a cooling effect which is visible to a distance of 60 m. Figure 6.1 shows a comparison between the resistivity

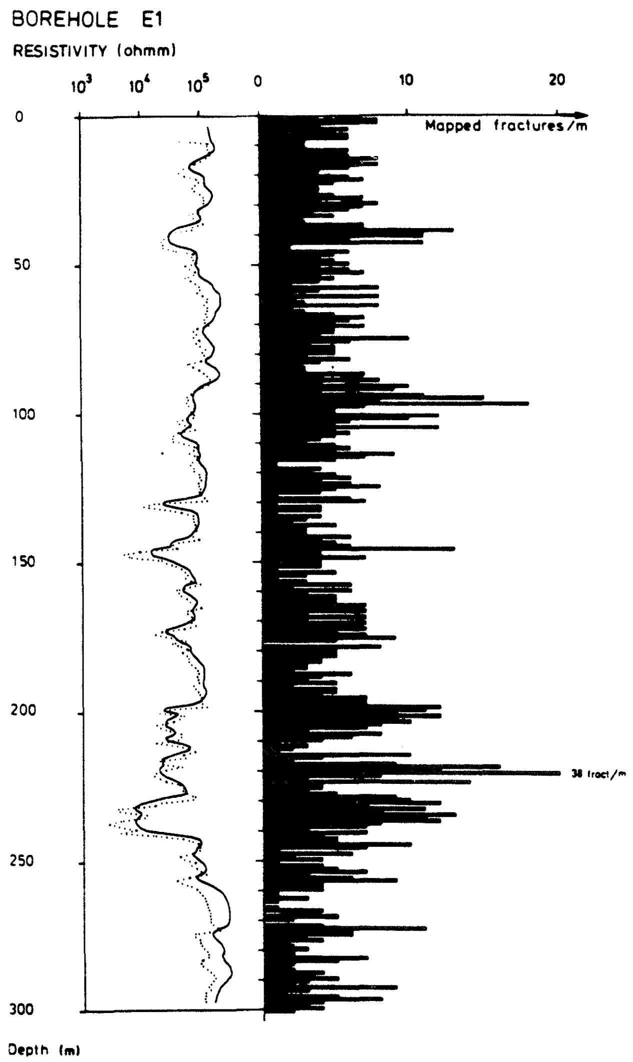

Figure 6.1. Comparison between resistivity logging results and fracture frequency in borehole E1. Solid line = normal resistivity, Dotted line = lateral resistivity.

log and the fracture frequency of the borehole. The radiation level varies between 100 and 160 uR/hour, which is about 1.5 to 2.5 times the background radiation in the rock. The increase is due to radon in the groundwater.

Borehole N1. The rock has a low fracture frequency which is reflected by the very high resistivity. A few minor fracture zones show however a decrease in resistivity. The temperature log indicates that the drift has caused an increased temperature gradient to a distance of about 60 m from the drift. This is due to a cooling effect by the ventilation of the mine. The radiation level is high in the borehole, about 250 uR/hour compared to an estimated background radiation of about 70 uR/hour. This increase is due to radon in the groundwater combined with a slow circulation rate of the water within the borehole. Figure 6.2. compares the resistivity log with the fracture frequency of the borehole.

Borehole V1. The radiation in this borehole is in the range 70-90 uR/hour, which is considerably lower than in boreholes N1 and E1. In this case the radiation level is in the same magnitude as the background radiation in the mine. For V1 this condition is probably an effect of the significant water inflow at the bottom of the borehole which creates a high circulation rate. The flow from the bottom up to the SGU-site level is estimated to take about 90 minutes in which case the radon will yield no additional radiation level.

The rock mass above 466 m (above the fractured zone in the lower part of the borehole) has a high resistivity which corresponds to a low fracture frequency. In the fracture zone the lowest resistivity is recorded in the whole logging program. The salinity increases with increasing depth, from about 700 ppm up to 2000 ppm. This indicates that the water inflow in the fracture zone is saline and on its flow the water is diluted with fresh, less saline water. The temperature gradient along the borehole amounts to about 9 ^{o}C/km, which is very low compared to normal conditions, an effect of the flowing water which smooths the gradient. Figure 6.3 presents a composite log of the geophysical results combined with information gained from the core-logging results.

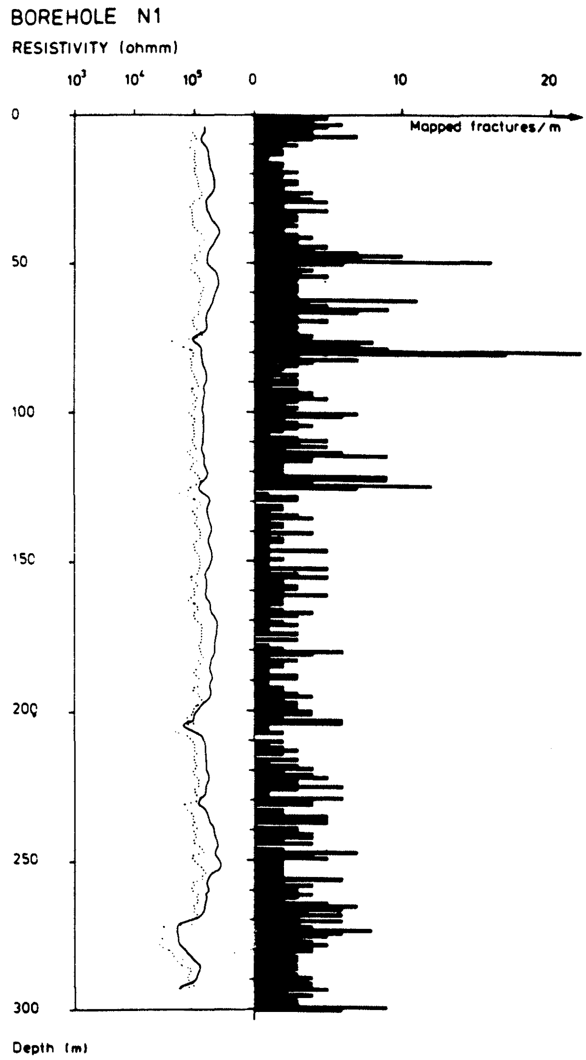

Figure 6.2. Comparison between resistivty logging results and fracture frequency in borehole N1. Solid line = normal resistivity, Dotted line = lateral resistivity.

Borehole V2. This is the deepest borehole in the Stripa area. According to the geophysical logging, this borehole may be divided into three separate parts. Down to 310 m the rock has a high resistivity and a radiation level at about 100 uR/hour. The salinity is fairly cons-

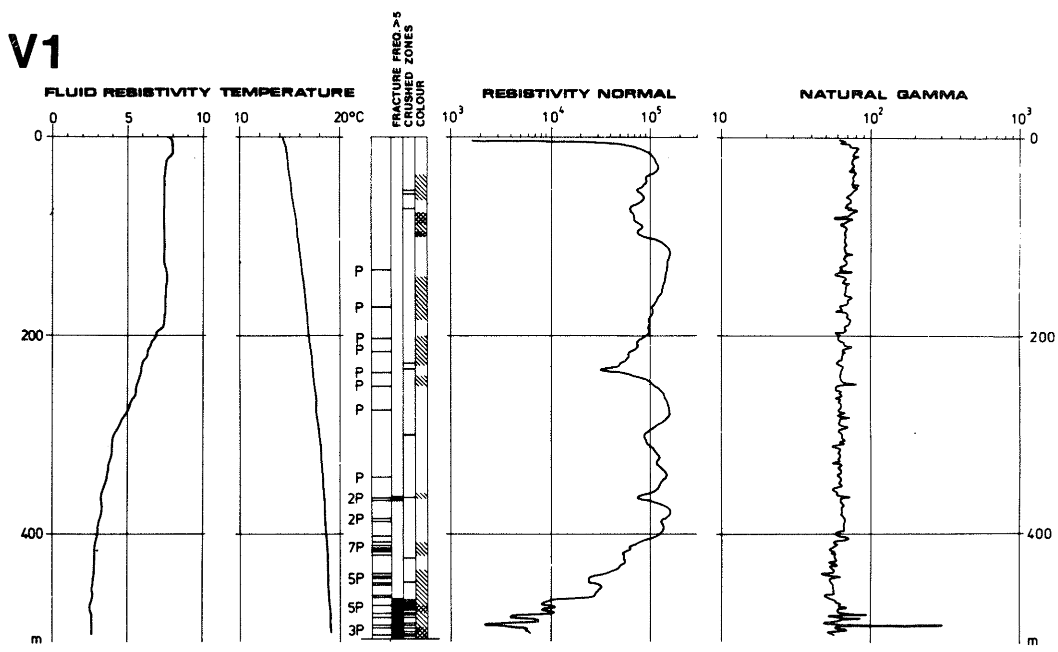

Fig. 4: Geophysical and core logs of the borehole V1.

Figure 6.3. Composite log from borehole V1 including both information from the geophysical logging and from the corelogging (Carlsson et al, 1983a).

tant at 700 ppm and the temperature gradient is high, about 17 $^{\circ}$C/km. Between 310 and 590 the resistivity is lower indicating an increased fracture frequency. The salinity is increasing from 700 ppm to 1050 ppm, and a number of local salinity peaks exist in connection with more fractured zones. The radiation level is in this section about 150 uR/min or about twice the background radiation.

The deepest part of borehole V2 is characterized by a higher resistivity and only a few minor zones of low resistivity are found. This is in agreement with the fracture frequency obtained from the core-logging, which shows that this part of the rock mass has a very low fracture frequency, below 1 fr/m in general. The radiation is low, about 80 uR/hour and the salinity is rapidly decreasing, from 1000 ppm to a few hundred ppm. However, local maxima are found in connection with more fractured parts of the rock mass. Figure 6.4 shows a comparison between different geophysical logs and information from the core-logging.

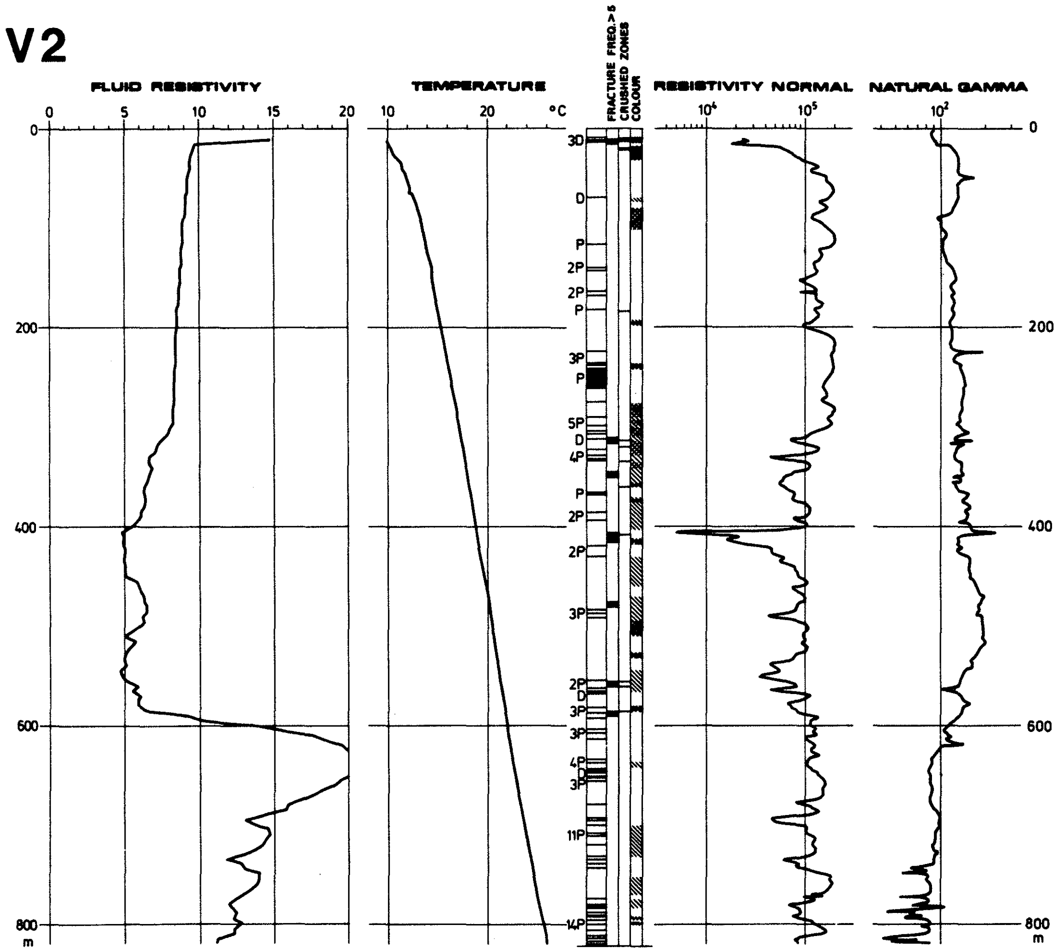

Figure 6.4. Composite log from borehole V2, including information from both the geophysical logging and from the core-logging (Casrlsson et al, 1983a).

6.2 Cross-hole measurements

The heavily fractured zone in borehole V1 which was unexpectedly encountered called for an interpretation of its orientation. Based on geological indications two main orientations were possible, i.e. N70E;60SE based on morphological and structural geological evidences or N40E;78NW based on mine mapping information. Also other orientations could be possible but less probable. In order to obtain additional information on the zone, different geophysical cross-hole methods were considered. Finally, an electrical method, the Mise a la Masse method was chosen due to its simplicity.

In the mise a la masse method one current electrode is located in a good electrical conductor such as a fracture zone. Another current electrode is placed as far away as possible from the first one in order to be effectively at infinity. The potential difference is measured between two potential electrodes. From model calculations of the potential field it is then possible to get an idea of the orientation of the electric conductive fracture zone. For the present purpose, the current electrode was located in the fracture zone in V1 and the potential field was recorded in boreholes V2, E1 and N1. A second measurement was made in which different indicated zones in V2 were used for the current electode.

The data measured in V2 with the current electrode in V1 are the most diagnostic as regards the orientation of the fracture zone. The model, with a strike of N40E with a dip of 70SE, gave the best fit to the recorded data. A model with the direction of N40E;70SW may also be roughly fitted. The result is presented in Figures 6.5-6.7, where different fracture orientations are matched against the recorded data.

The mise a la masse measurements present results which are in agreement with the previously described geological data. The geophysical interpretation indicated that

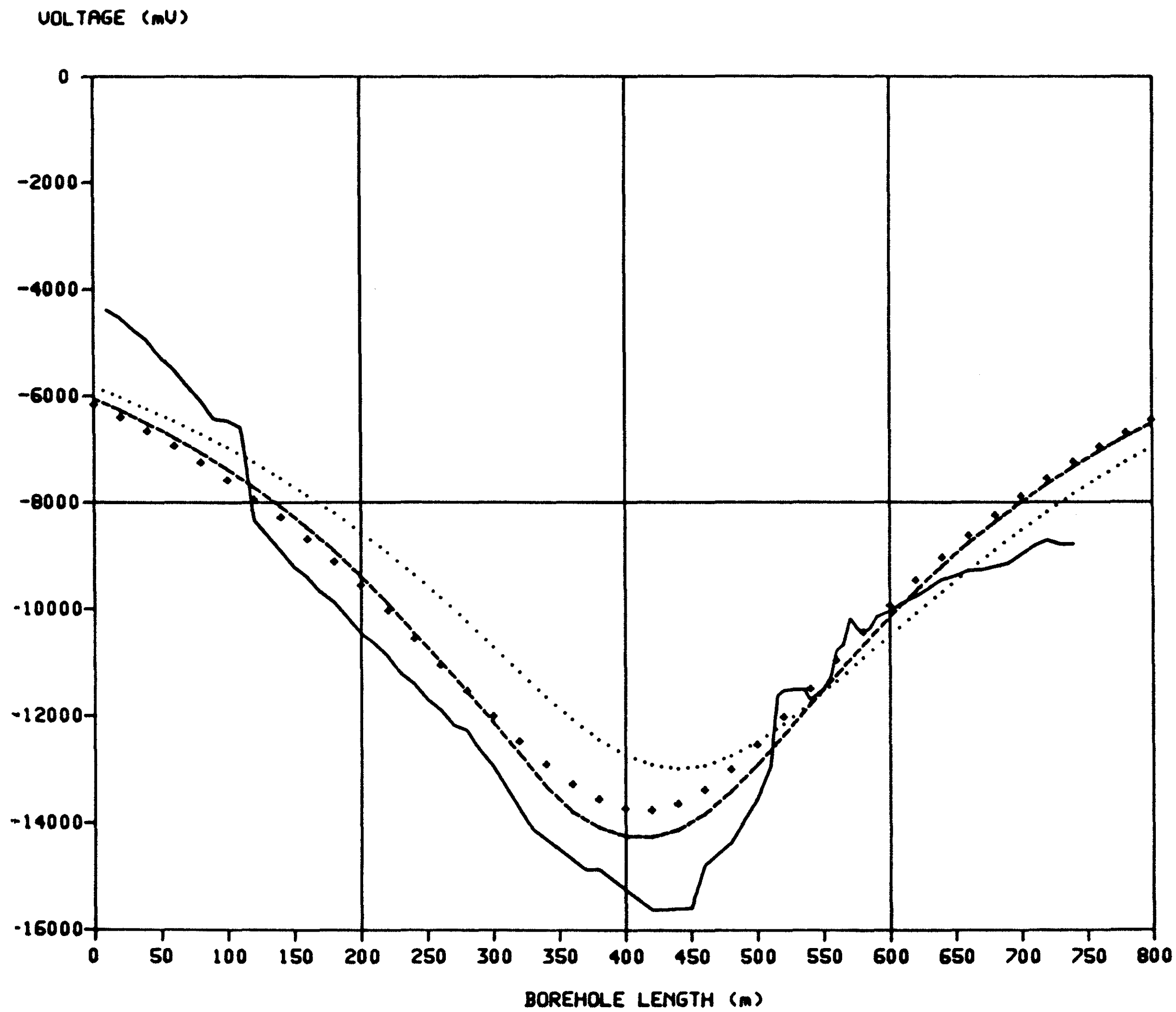

Figure 6.5. Measured and calculated potential data in V2 for different orientations of the fracture zone. Solid line: measured data, Dashed line: N40E;70SE. Dotted line:N40E;75NW. Crosses: N20W;75NE.

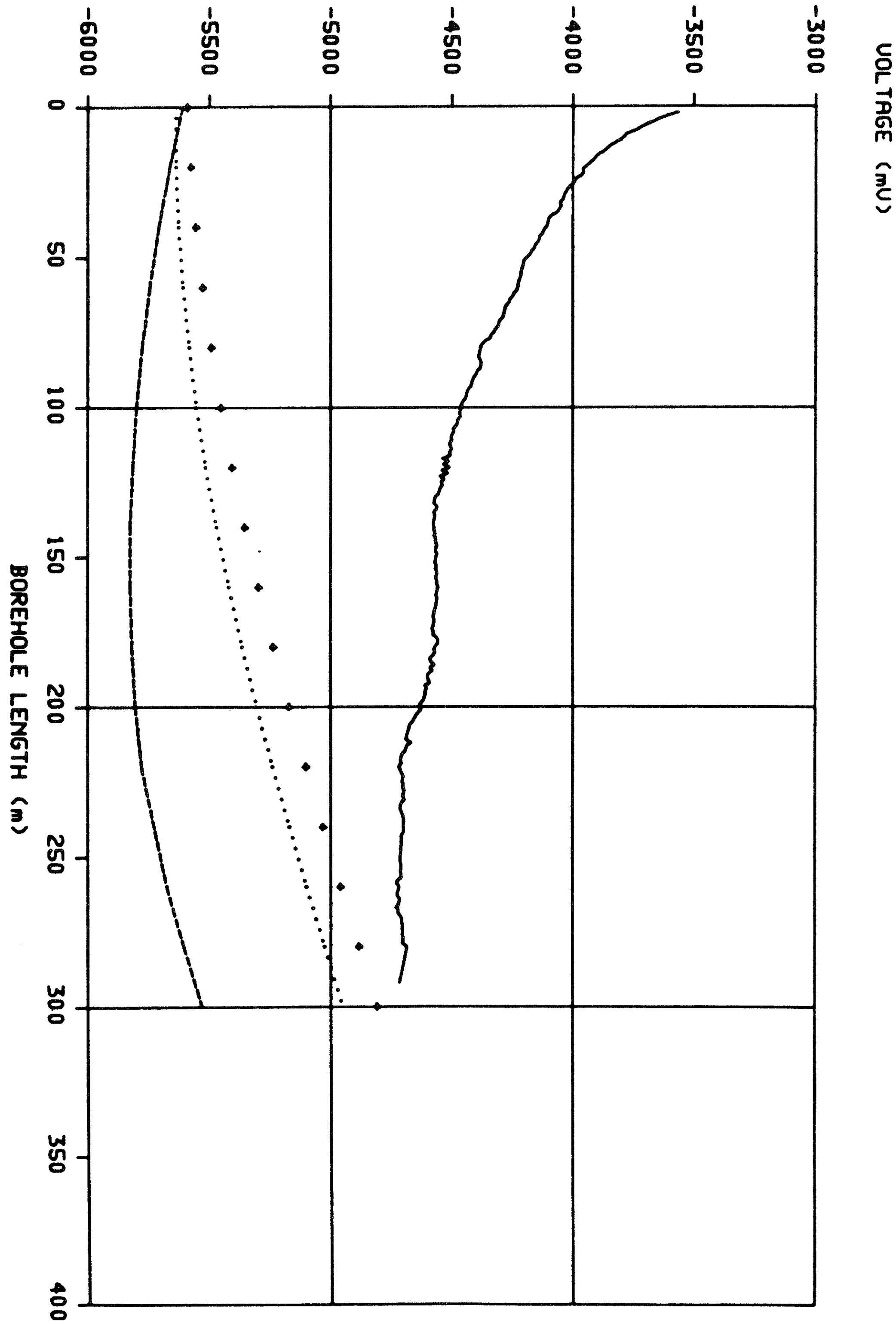

Figure 6.6. Measured and calculated potential data for N1 for different orientations of the fractured zone. Solid line: measured data. Dashed line: N40E;75SE. Dotted line: N40E;75NW. Crosses: N20W;75NE.

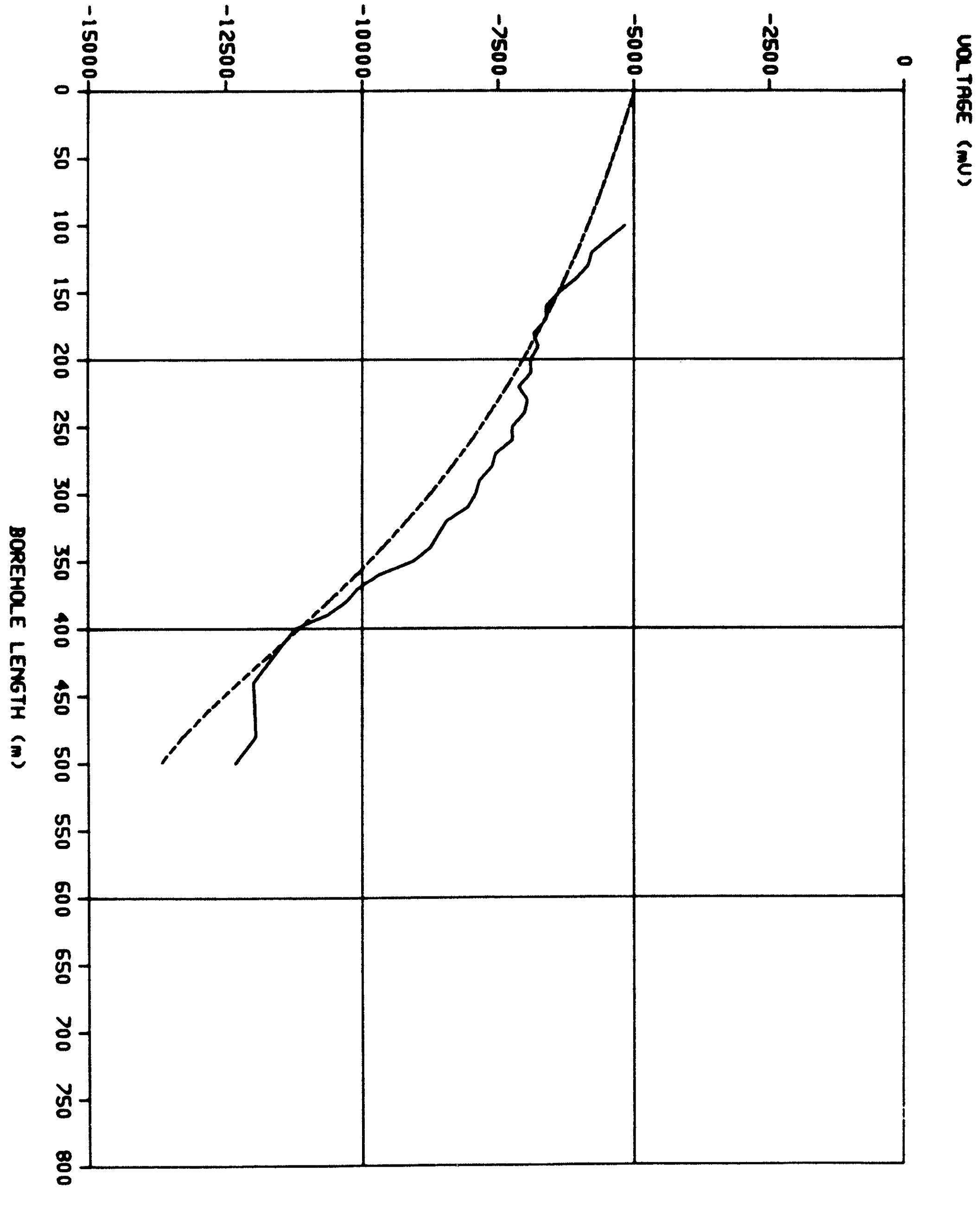

Figure 6.7. Measured and calculated potential data in V1 for the orientation N40E;70SE.

the orientation of N60E;60SE is the most probable orientation. This value should be compared to N70E;60SE which is the most probable geological interpretation.

6.3 Conclusions

Geophysical measurements were useful in the interpretation of the hydrogeological conditions in the Stripa mine. The results were used as a basis for the selection of zones for hydraulic testing, and the techniques were of significance for the deduction of the penetrated fracture zone in borehole V1.

However, not all of the parameters included in the standard logging program yielded information of importance. Below is a validation of the various logs and their capability of yielding information of importance from a hydrogeological viewpoint.

The resistivity logs provided the most information about the fracturing. There is a close correspondence between increased fracturing and decrease in resistivity. However, it should be noted that the resistivity logs do not provide information on the water-yielding capacity of the deduced zones, but they indicate the potential for a water yielding zone. The correlation between fracture frequency, resistivity and hydraulic conductivity has been studied in considerable detail by Magnusson and Duran (1984). They found that there existed a good correlation between fracture frequency and resistivity, but poor correlation between those two parameters and the hydraulic conductivity.

Also the cross-hole electrical method used turned out to be an useful tool. In this case the method was used to deduce the orientation of a fracture zone about which very little was known. The results have later been supported by radar measurements carried out in borehole V1, which also yield a similar orientation as the mise a la masse technique

The natural gamma log gave an indication of the radiation level in the boreholes. The combined effect of different radiation sources were recorded. The value of this log is that it may be of importance for the interpretation of radiogeological data regarding the groundwater isotopes. The location of pegmatites could also be identified by this log.

The temperature and the borehole fluid resistivity yielded information on water-yielding fractures and fracture zones. These logs give information more related to the hydrogeological conditions compared to the other logs. These logs also yielded valuable information regarding the hydrogeochemical part of the investigations.

7. HYDROGEOCHEMISTRY

The hydrogeochemical work is reported in a separate report (Stripa Project TR 85-06) to which the reader is referred.

8. HYDROGEOLOGICAL INVESTIGATIONS

8.1. Testing design

The groundwater conditions around the Stripa Mine are affected by the mining activities. The groundwater system has almost continuously been in balance with the drainage from the underground drifts, i.e. the groundwater system is in a quasi-steady state condition.

A number of techniques may be applied to the underground hydraulic testing. However, requirements and demands from other activities and research programs make some of these techniques less suitable. In order to obtain accurate water sampling and analyze results, any introduction of foreign water should be avoided. This condition calls for a testing technique where the groundwater should be extracted rather than injected. Other test programs within the Stripa project, as for instance, the Buffer Mass Test, are strongly dependent on an undisturbed supply of groundwater and pressure build-up, which calls for a minor extraction and disturbance on the water head around the mine.

The hydraulic testing takes place deep underground, in the potential sink made up by the mine, and it was found convenient to use the natural drainage for water extraction as the main tool and to measure the pressure build-up after shut-in or fall-off after release. By this technique, no foreign water is introduced into the groundwater system, and the disturbances on the head should be limited. This technique was used as the main tool both in single hole tests and in interference tests between different boreholes. However, as a test effort water injection tests were carried out at the end of the investigation period in order to test the applicability of these techniques in an underground environment.

Thus, in summary three different test approaches were used as:

1. Build-up tests
2. Injection-recovery tests
3. Interference tests

8.2. Equipment

8.2.1 Equipment for build-up and interference tests

The equipment for build-up and interference tests consists of a double packer system with a downhole probe containing the pressure transducers. The system is hoisted either by wire or pipe line, depending on the inclination of the boreholes (Jacobsson and Norlander, 1981).

The equipment in total consists of a downhole probe containing two pressure transducers and one thermo-element. The probe is downwards connected to a double-packer system and upwards to a surface controlled valve used for shut-in tests. In Figure 8.1, a schematical view of the equipment during testing is given.

The packers are operated from the surface with gas through a nylon tubing. When inflated, the packers enclose two test sections; one between the packers and one between the bottom packer and the bottom of the hole. These two sections are connected via 1/8" steel tubings to the pressure transducers in the probe. From each sealed off section water samples can be collected through 1/4" nylon tubings going to the surface.

The downhole electronics are connected through a 12-conductor cable to the surface equipment. The downhole equipment consists of a probe for the pressure transducers and the thermo-element, packers and a downhole valve. Kistler 50 and 100 bar FSO (fullscale output) piezoresistive transducers measuring absolute pressure are used for the pressure recordings. The system has an accuracy of 0.1 % FSO or better.

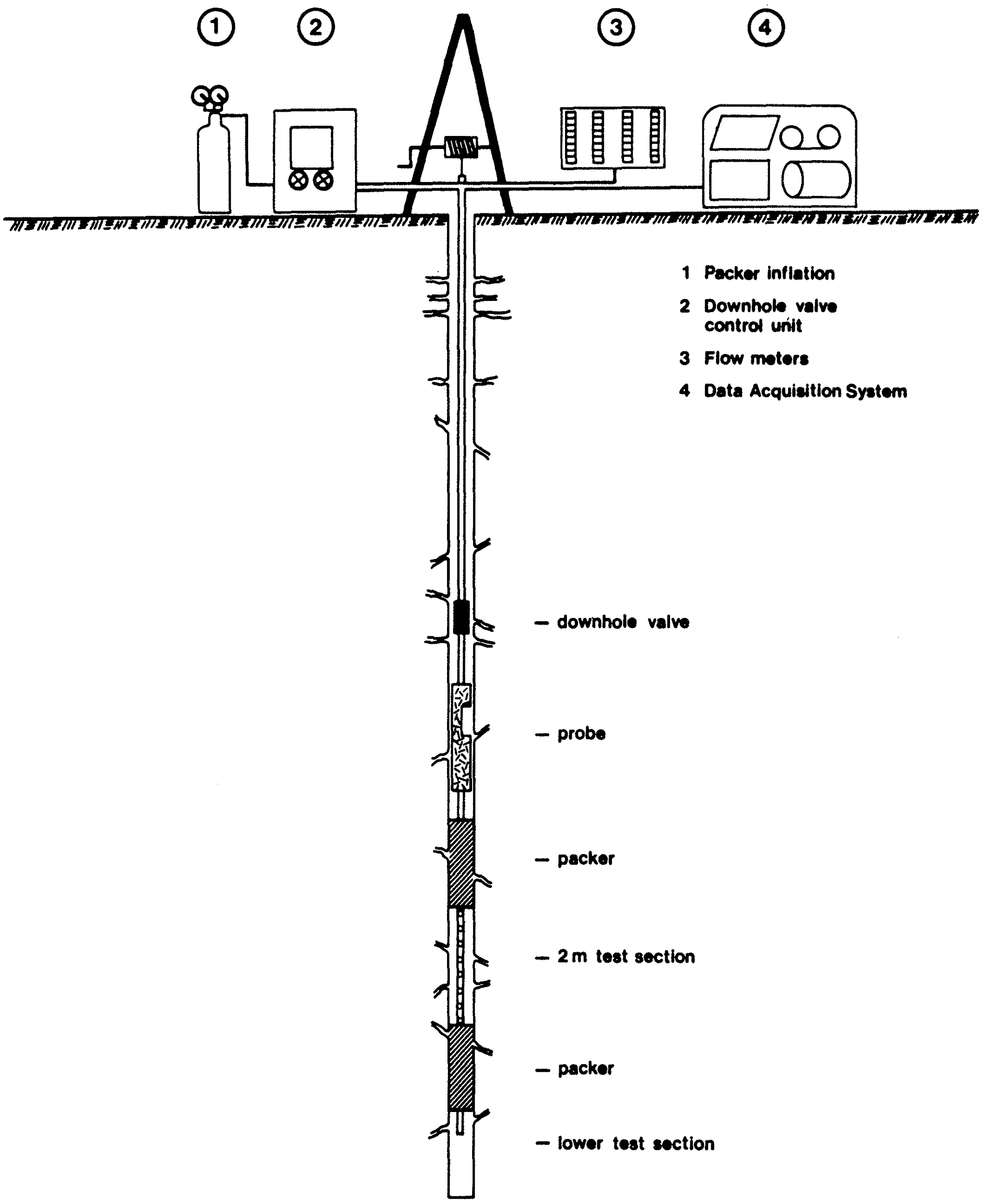

Figure 8.1. Schematic view of the equipment used during build-up testing.

The packers chosen are Lynes surface controlled injection packer (SCI PIP) with a maximum working differetial pressure of 380 kp/cm^2 (5 500 PSI). The system is inflated by nitrogen gas from the surface. During the testing the packers were inflated at 180 kp/cm^2.

The compressibility of the test equipment used was found to be in the order of $3\ 10^{-9}\ Pa^{-1}$, that is 6 times the compressibility of water. The downhole equipment is controlled and recordings taken through a data acquisistion system (DAS) at the surface. A datalogger provides the basis of the DAS.

For one of the interference tests (no 2), a modified design was used in order to pack off a number of different sections in each borehole. In this case a straddle packer equipment was used consisting of four packers, giving four test sections in each hole, each of which connected to a system of pressure transducers. By this system, each test section was individually monitored. A system of electromagnetic valves located outside the boreholes made it possible to monitor 12 test sections with only 3 trancducers.

For another interference test (no 3), where the boreholes at the BMT-area acted as receiver holes, the installed transducers and manometers at the BMT-area were used for pressure monitoring. However, in order to obtain a more well-defined time resolution some of the manometers were equipped with pressure transducers and connected to a second data logger.

8.2.2. Equipment for water injection tests.

The equipment used for the injection tests consists of a pipe string system (c.f figure 8.2). The following component parts are included in the equipment:

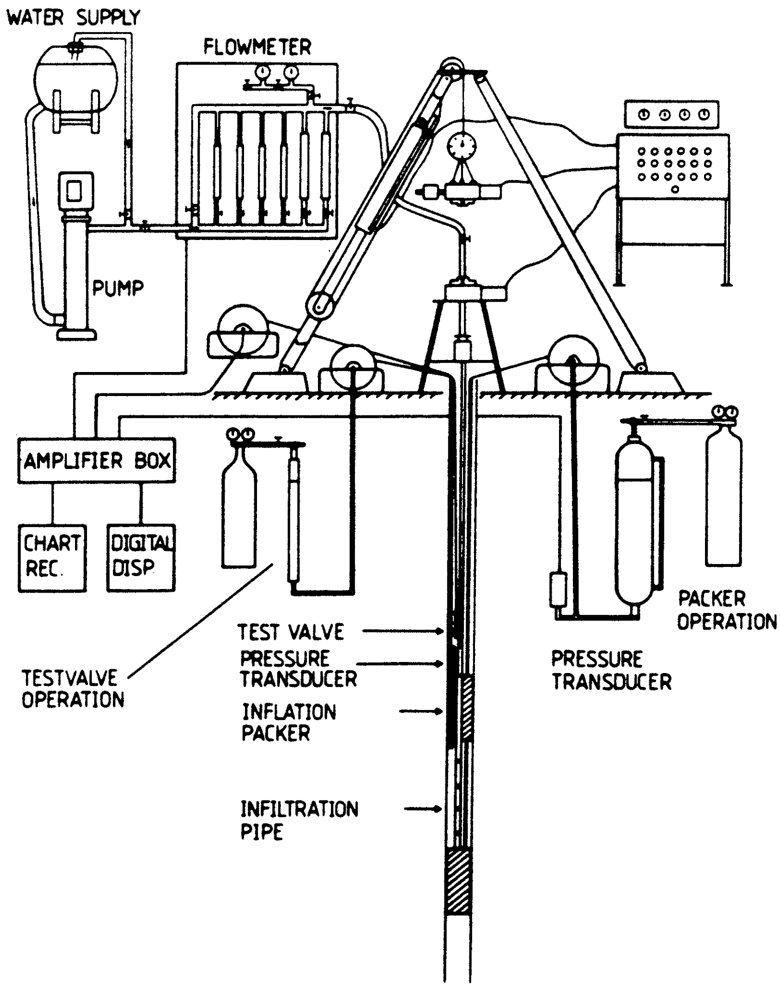

Figure 8.2. Schematic view of the equipment used during injection-recovery testing.

- downhole equipment
- surface unit
- communication equipment
- data acquisition system

A detailed description of the equipment is given by Almen et al (1983). The downhole equipment consists of a double packer system with a packer spacing of ten meters, injection pipes, pressure transducer, and test valve. The surface unit consists of regulating equipment for packer inflation and valve, pump, flow meter system and electronic system for the pressure transducer.

The communication system consists of a steel pipe string for the water, hydraulic tubes for packer inflation and valve regulation and signal cable for the pressure transducer. Included in the surface equipment is also the data acquisition system which contains a data-logger, printer, and data-recorder.

The test section is sealed off by the two packers separated by a distance of ten meters. The packers are inflated by applying a nitrogen gas pressure through the inflation line. Laboratory tests have shown that the packers seal at an overpressure of 0.4 MPa, but in order to achieve as rigid equipment as possible an overpressure of 1.5 MPa was used.

The pipe line is equipped with a hydraulic valve down at the uppermost packer. The actual head down in the test section is recorded through a piezoresistive transducer down at the test section. The accurracy of the system is < 0.5 % in its original layout. However, the accurracy is increased by calibration of the transducers against an especially designed calibration system.

The flow meters used for recordings of the water flow during the injection consist of five individual recorders connected in parallel which gives a total range of $1.5\ 10^{-9}$ - $2.5\ 10^{-4}\ m^3/s$. These meters are read manually, as well as the change between different meters.

8.3. Tests performed

The tests performed in the program can be divided into single and multiple-hole tests. In total the following tests were conducted within the program:

* Single hole tests
  - Build-up tests in selected sections of borehole E1, N1 and V2.
  - Injection and recovery tests in 10 meter sections in borehole E1, N1 and V1.

* Multiple hole tests (interference tests)
  - Fall-off and recovery tests between borehole V1 and V2 and between borehole N1 and the BMT-area.

The results of the different tests are presented by Carlsson and Olsson in two reports on hydraulic testing (1985a and b).

8.4. Build-up tests

The pressure build-up tests were performed as single hole tests where the pressure change in a sealed off section was monitored. The tests were carried out only for selected sections of the boreholes.

The packer system consisted of two packers. When the packers were inflated, the flow from the innermost test section, i.e. between the inner packer and the bottom of the hole, was shut off and the pressure in this section began to increase. The main test section, between the packers, continued in free flowing conditions and the flow rate was recorded. After a flowing period of at least half a day, the downhole valve was closed and the actual build-up test started. The pressure build-up in the main test section continued for about five days after which the valve was reopened. During the test, the pressure build-up in the main test section as well as in the inner section was monitored. Schematically, the

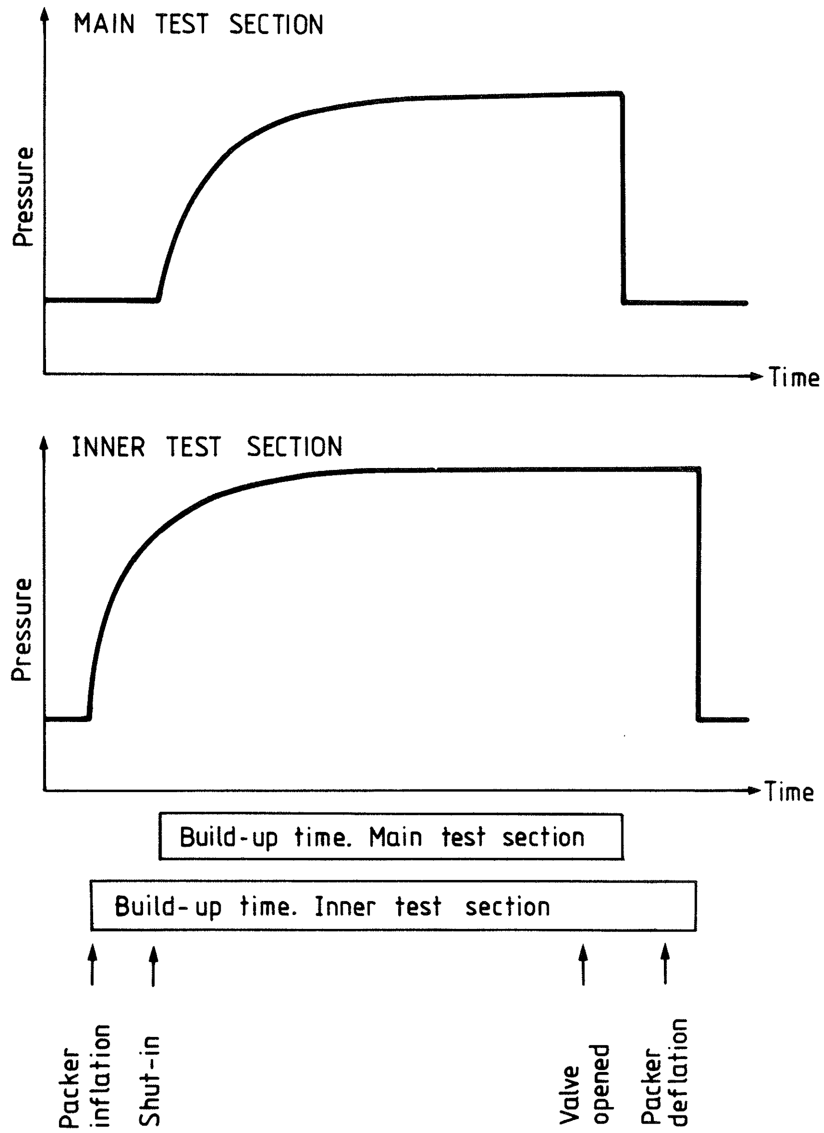

Figure 8.3. Pressure variation versus time for a complete cycle of a shut-in, build-up test.

pressure variations in time during a complete cycle is illustrated in Figure 8.3.

Build-up tests were performed in selected 2 meter sections in borehole E1 and N1 and in selected 3.7 m sections in borehole V2. The test sequence started with the section nearest to the site and continued along the borehole. This gave time for the natural pressure around the borehole to rise to its "natural undisturbed" value before the actual test in the selected section was performed.

The tests performed were evaluated first considering flow regimes and secondly considering wellbore storage and skin. The first procedure used follows that described by Raghavan (1976) with some exceptions. The data were plotted in order to evaluate if linear, radial or spherical flow prevailed. However, wellbore storage and skin effects influenced the pressure behaviour. Wellbore storage or afterflow was observed as a straight line in a log-log graph of pressure versus time. During this period the formation and the type of flow into the wellbore play no part. In order to take into account the effects of wellbore storage and skin, another evaluation technique was also used, based on type-curve matching.

In total 29 build-up tests were performed. From the interpretation carried out with due consideration to the wellbore storage and skin, the hydraulic conductivity values ranged from $6\ 10^{-13}$ m/s up to $3\ 10^{-8}$ m/s. The tested sections were chosen from geophysical and corelogging results in order primarily to represent zones of high fracturing and expected high values of the hydraulic conductivity.

Criteria are given in the literature on the duration of the flowing period prior to the build-up period. For practical purposes, the build-up data can be matched with type-curves (Agarwal et al 1970) where the effect of the wellbore storage and skin is taken into consideration if the following criterion is fulfilled regarding the flowing period (Raghavan 1980):

$$t_{Dp} > 50\ C_D \qquad (8\text{-}1)$$

where t_{Dp} is the dimensionless flowing time and C_D

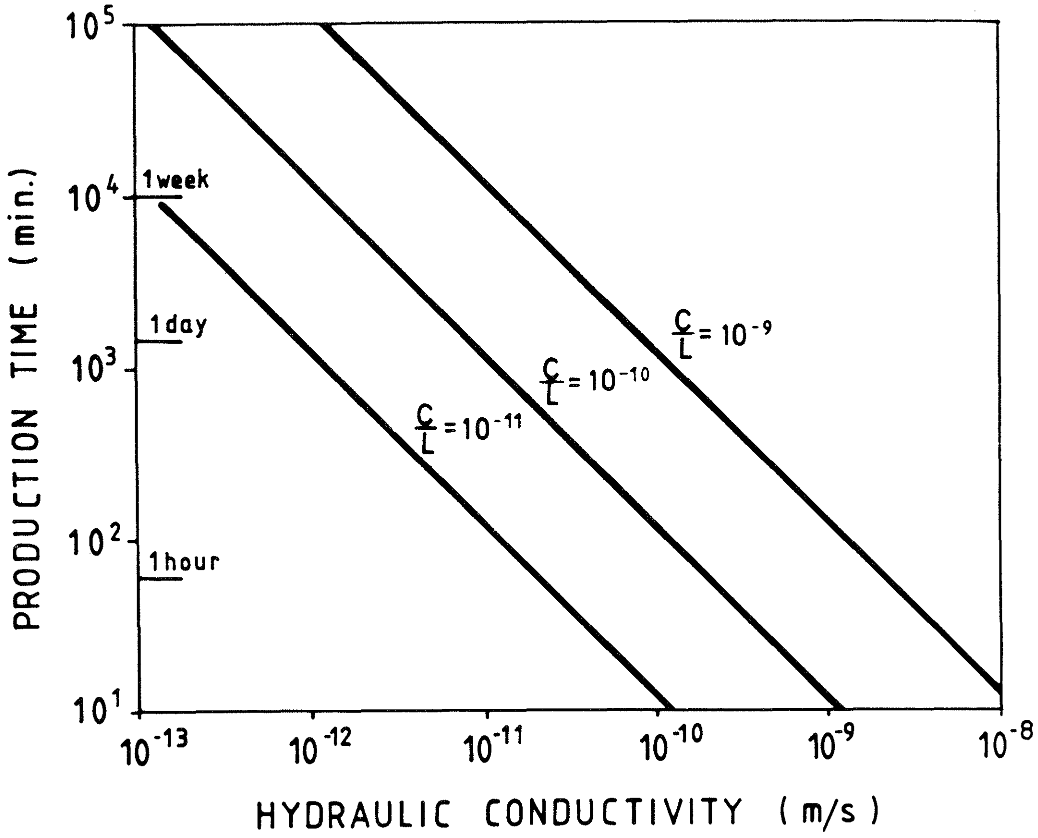

Figure 8.4. Relation between hydraulic conductivity and required flowing time prior to shut-in.

is the dimensionless wellbore storage.

The relation between the hydraulic conductivity and the required flowing time prior to shut-in is given by Figure 8.4 for different values of C/L. The median value of the wellbore storage coefficient $C = 3.10^{-11}$ m^3/Pa implies that a flowing period of 1-2 days is required prior to the build-up periodwhen the hydraulic conductivity is in the range of 10^{-10} m/s. The flow value to be used in the calculation should be the instantaneous rate at the time of shut-in. In Figure 8.5 the test sequence in a build-up test is schematically illustrated.

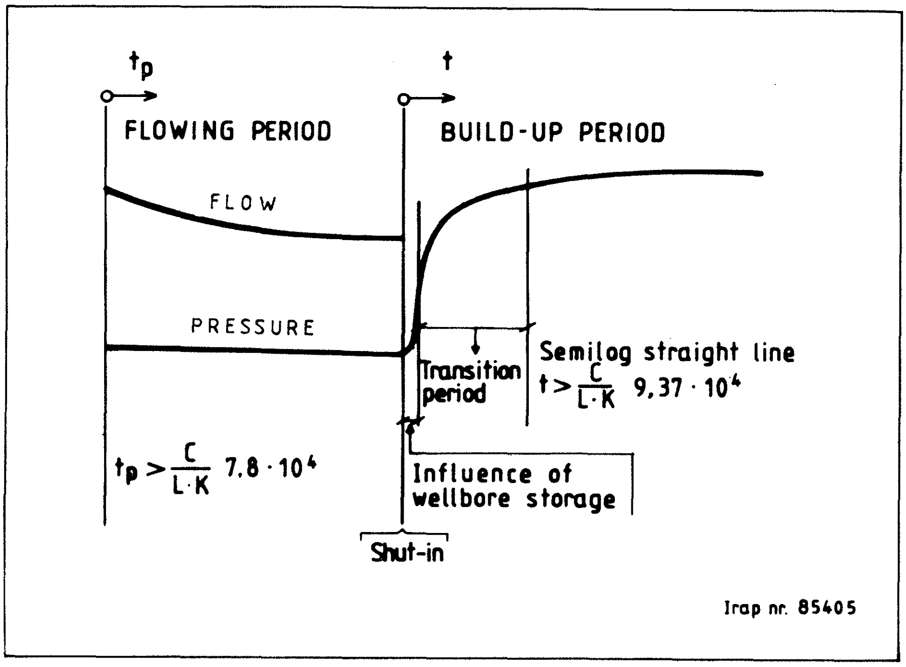

Figure 8.5. Test sequence in a build-up test with different requirements set up.

In the cases where wellbore storage dominates pressure data and testing is conducted long enough, two semi-log straight lines are usually obtained (Gracia-Riviera and Raghavan 1979). The second straight line is the correct one if no boundary effects interfere with the test. In the case of short time pressure data dominated by wellbore storage and skin, the first straight line may be chosen as the proper line erroneously. In Figure 8.6 a crossplotting is shown of the different values obtained on the hydraulic conductivity by semilog straight line and type curve matching. The former values are in most

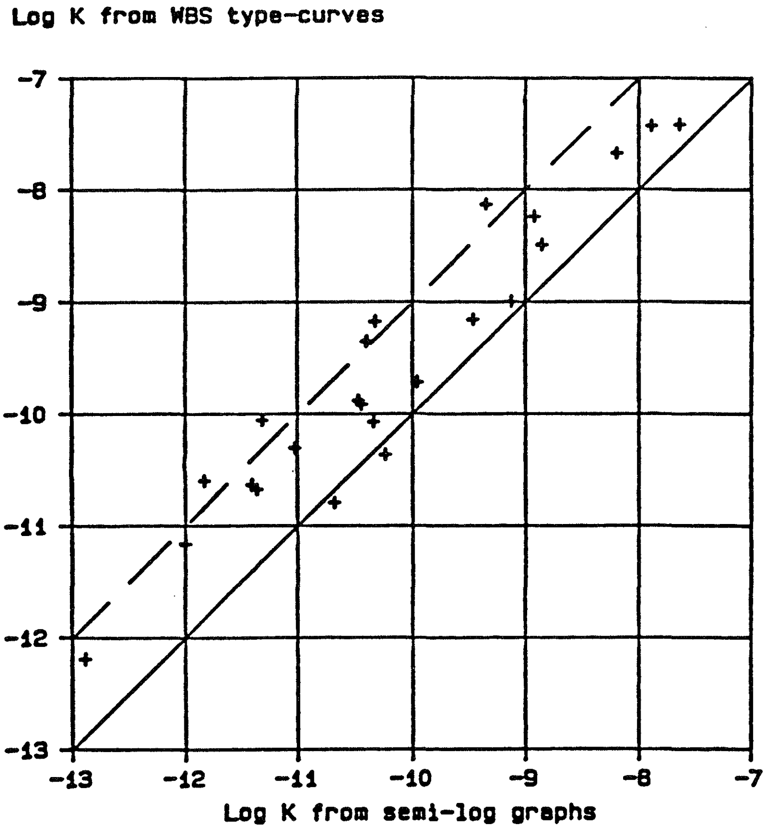

Figure 8.6. Hydraulic conductivity obtained from straight line versus matching with due consideration of wellbore storage and skin.

cases 0.1-0.3 times lower. Thus an interpretation without due consideration of wellbore storage and skin will underestimate the hydraulic conductivity by a factor of about 3-10.

Two main types of data curves were observed in the interpretation. In the most common one, the curves had a unit slope in the early time data and a radial flow behaviour in the later part as illustrated in Figure 8.7. The second type had no unit slope in the beginning, instead the slope indicated a linear flow behaviour

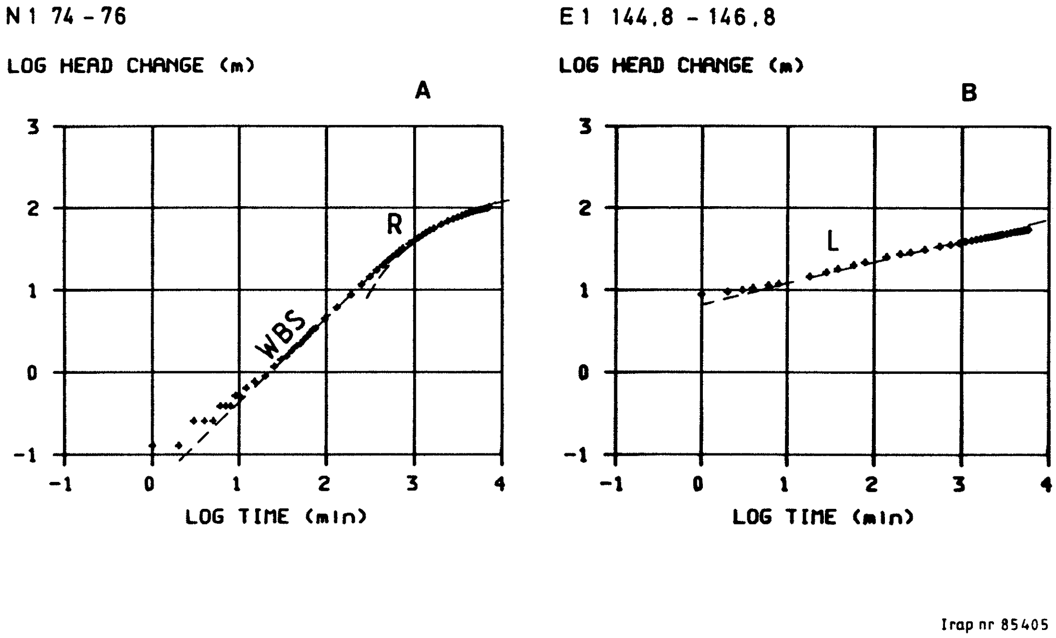

Figure 8.7. Examples of the two main types of data curves obtained from the build-up tests. A. Curve with wellbore storage during long test time (N1 74-76 m). B. Curve indicating linear flow behaviour in early time data (E1 144.8-146.8 m).

which in the later part was transferred to a radial flow, c.f. Figure 8.7. This type of curves had in general a negative skin indicating that fractures closely interact with the borehole. The first type of curves usually had positive or zero skin.

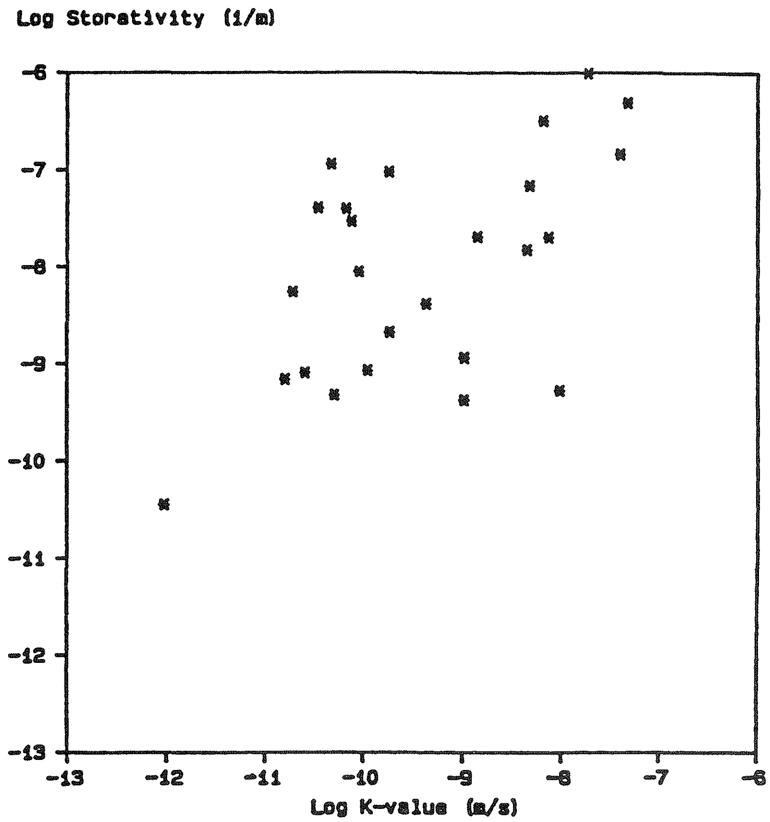

Figure 8.8. Specific storage coefficient versus hydraulic conductivity obtained from build-up tests.

From the interpretation, values of the specific storage coefficient were estimated. These values are presented in Figure 8.8 in relation to the corresponding the hydraulic conductivity.

Two build-up tests of very long duration were performed prior to the interference test no 1, c.f. section 8.6. The first one comprised the highly fractured part in the bottom of borehole V1 and the second, the section 356-471 m in borehole V2 i.e. on the mine level corresponding to the highly fractured zone in V1. In both sections the

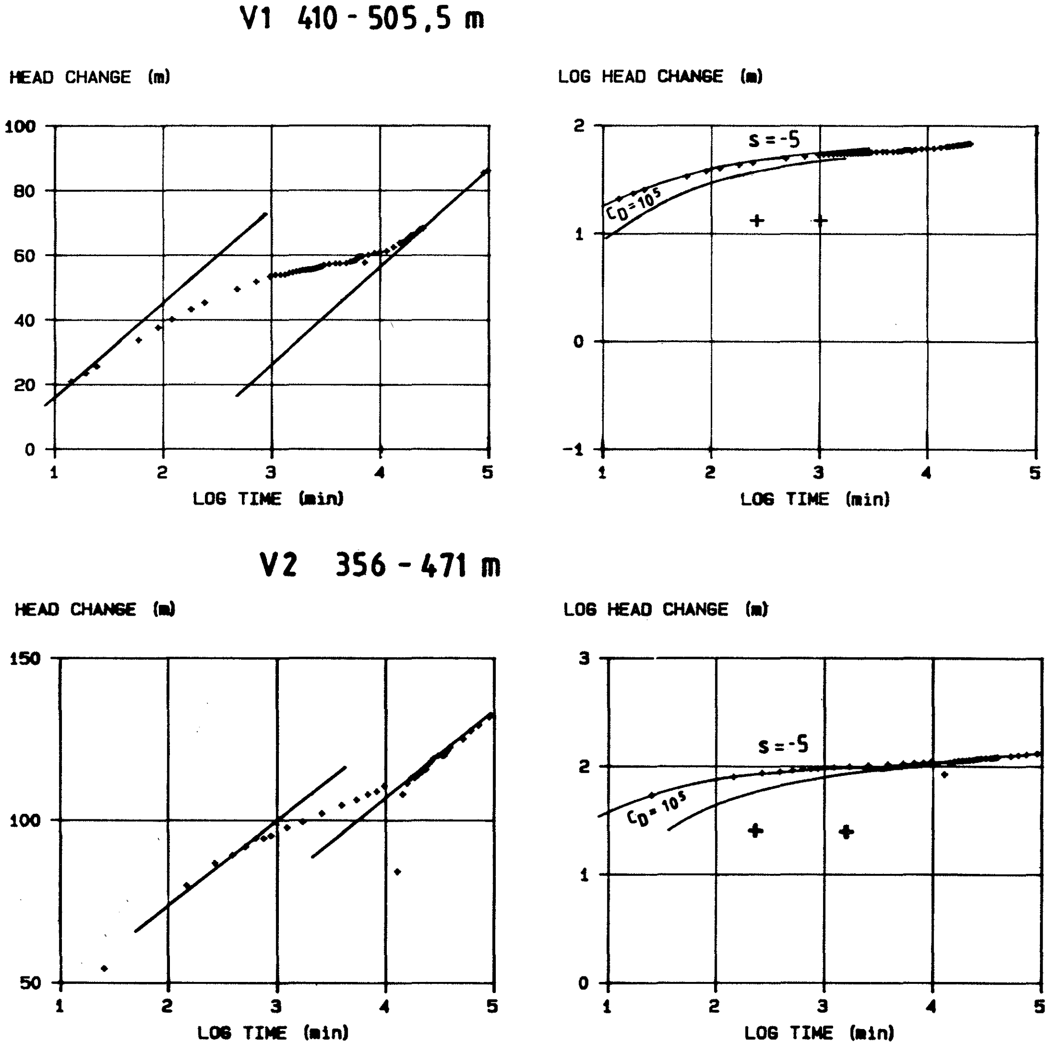

Figure 8.9. Graphs of pressure versus time from build-up tests showing double-porosity behaviour.

build-up curves showed a double porosity behaviour with the hydraulic parameters given in Table 8.1. Figure 8.9 illustrates the double porosity behaviour in the data-curves.

Table 8.1. Values of hydraulic conductivity and specific storage coefficient from data showing double porosity behaviour in build-up tests in V1 and V2.

Test section	K-value m/s	Spec. storage coefficient primary 1/m	secondary
V1 410-505	$1.0\ 10^{-7}$	$1.1\ 10^{-7}$	$8.0\ 10^{-7}$
V2 356-471	$1.4\ 10^{-10}$	$2.6\ 10^{-10}$	$1.7\ 10^{-9}$

8.5. Water injection tests

Water injection tests were carried out in borehole E1, N1 and V1. These tests were made as hydraulic loggings of the entire boreholes in 10-meter sections.

The tests were initiated with a short build-up period after which the water injection started and continued for 2 hours. The injected flow-rate was monitored continuously during this time. A two hour or longer period of pressure fall-off (recovery) monitoring completed the test cycle. In order to identify the pressure transience on which the injection was superimposed, the information from the initial stage and the fall-off period was analysed with respect to the formation pressure build-up. A pressure distribution versus time as schematically given in Figure 8.10 was obtained for each test section.

The total testing time for a ten meter section required on average one working day including installation and testing.

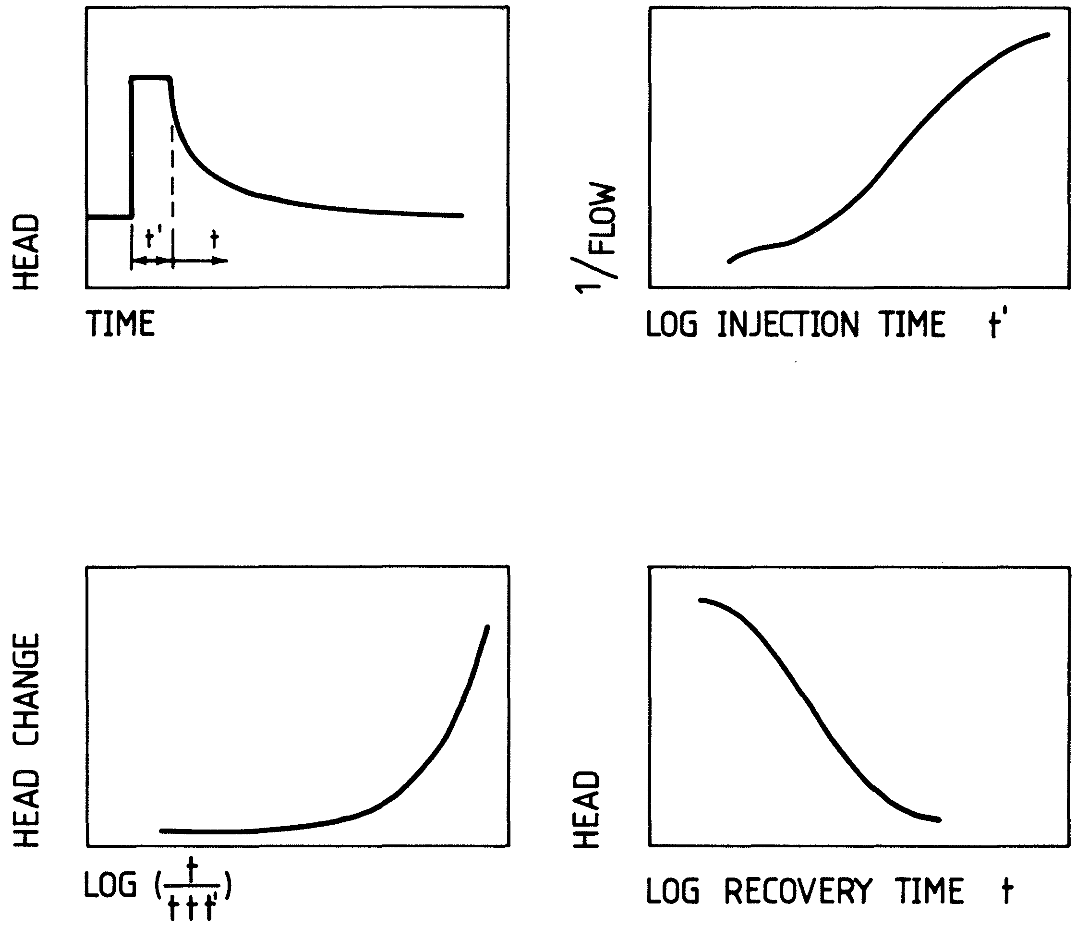

Figure 8.10. Different graphs used for the interpretation of the injection-recovery tests.

The results and experiences gained from these tests all pointed at the importance of having achieved steady state in the natural formation pressure in the test section prior to any testing. In horizontal boreholes this requirement is even more pronounced since the natural head in these boreholes usually is less disturbed by

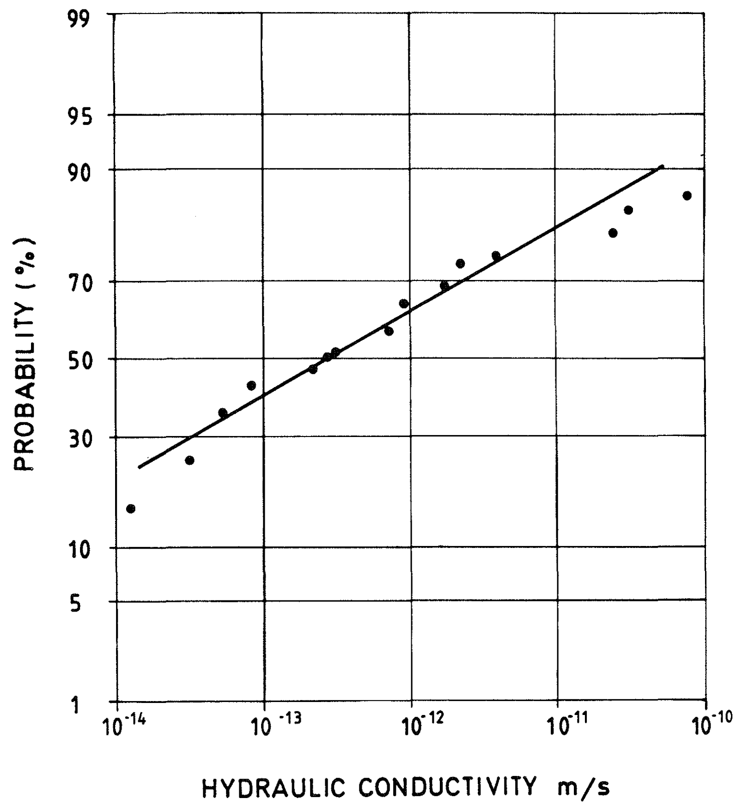

Figure 8.11. Frequency distribution of hydraulic conductivity in 10 m sections in borehole V1 down to the highly fractured zone.

the underground constructions at longer distances from the mine than in vertical direction. Thus in the two horizontal boreholes E1 and N1 only a limited amount of reliable data were obtained. In the vertical borehole V1 a complete 10 m section logging of the borehole was possible to obtain. The interpreted hydraulic conductivities covered a range of more than seven orders of magnitude. In Figure 8.11 a frequency distrubution of the 10 m sections down to the highly fractured zone in bore-

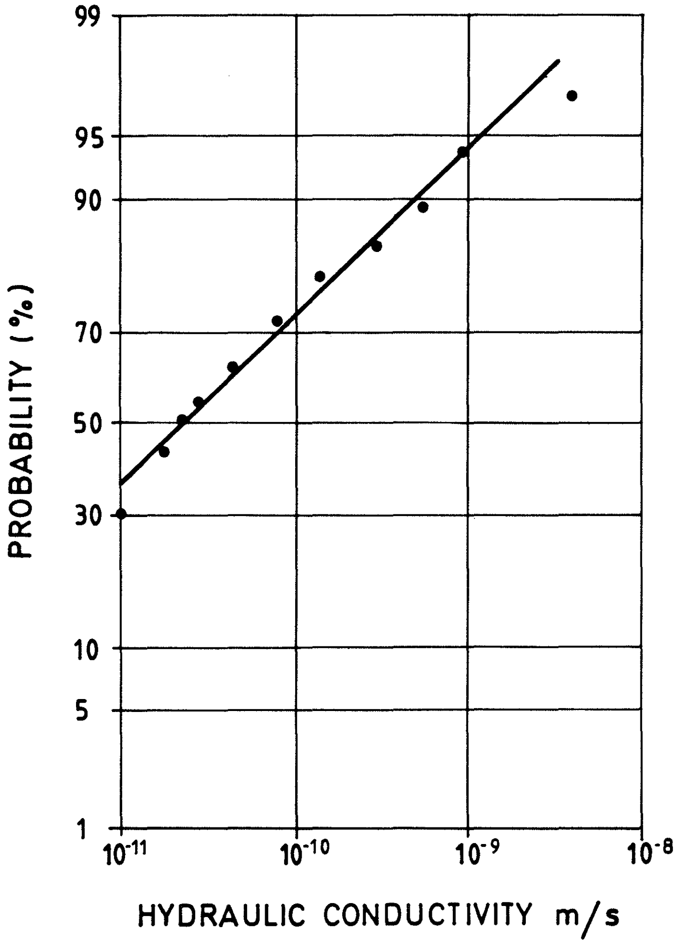

Figure 8.12. Frequency distribution of hydraulic conductivity in 6.6 m sections in borehole V2 between 2 and 463 m length.

hole V1 is given. The median value calculated is about 2.8 10^{-13} m/s. This value could be compared to the median value of 2.2 10^{-11} m/s obtained from 6.6 m test sections in the borehole V2 between 2 and 463 m tested in the SAC period, c.f. Figure 8.12.

The values of the hydraulic conductivity were calculated both from the injection and the recovery phases. A com-

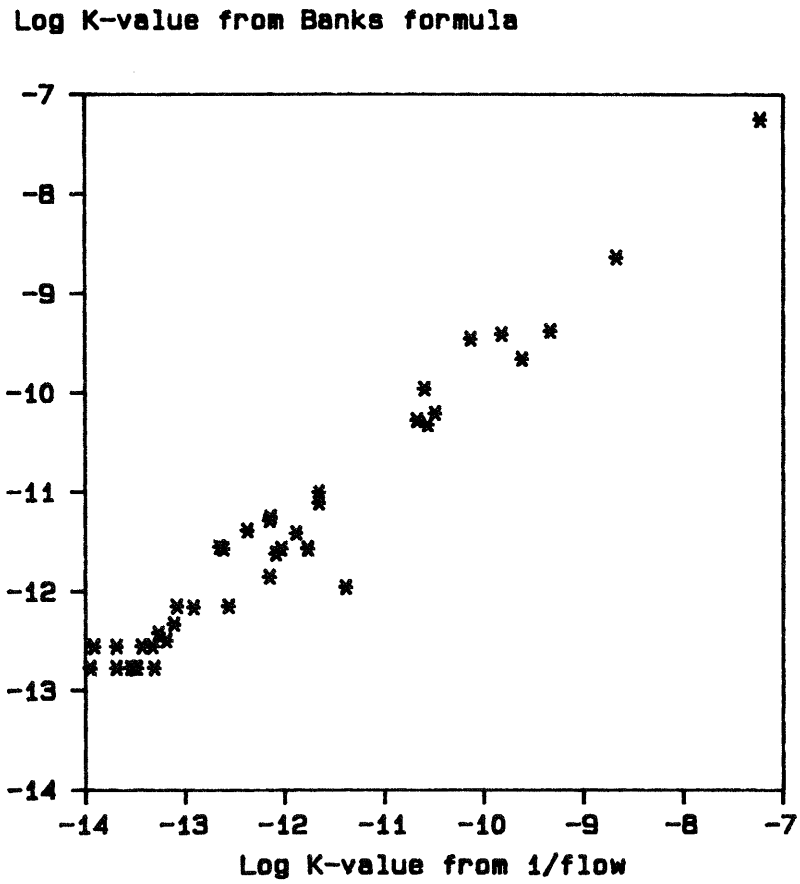

Figure 8.13. Hydraulic conductivity values obtained from transient solution versus from pseudostationary solution.

parison was also made with values calculated by the pseudostationary formula by Banks (Moye 1967). In general the later values (K_B) were higher than the values from transient evaluation using flow versus time (K_f). In Figure 8.13, the relation is presented between the two K-values. This relation can be expressed by the following equation:

$$K_B = 0.1\ K_f^{0.86}$$

8.6. Interference tests

Three different interference tests were conducted within the program. These tests were focused on the interconnections between highly conductive zones in one borehole and parts of other boreholes. Thus, the conductive zone in the lowermost part of borehole V1 and the innermost part of borehole N1 were used as source sections in the following interference tests:

* Interference test no 1 between V1 and V2
* Interference test no 2 between V1, V2, N1 and E1
* Interference test no 3 between N1 and the BMT-area

In Table 8.2 the different sections included in each test are listed together with the distances from the source borehole. The distances are given in meters from center to center of each section.

Each test started as pressure build-up tests, however with a much longer build-up period compared to regular build-up tests. In this case the build-up period continued until quasi-stationary conditions were obtained in the included test sections. At most, a build-up period of three months preceeded the actual interference test.

After the build-up period the pressure in the selected source section was released and the resulting pressure changes in the receiver sections were recorded. The conditions in the source section were either free flowing or flowing at constant rate which continued over a long period of time, normally as long as the build-up period.

Table 8.2. Data of interference tests performed.

Test no	Source	Type of source	Receiver borehole	Duration days
1	V1, 410-505	Free flowing 40 l/min	V2, 356-471 m	60
2	V1, 455-505	Constant rate 7 l/min	V2, 4 sections N1, 4 sections	42
3	N1,	Free flowing 1.1 l/m	BMT 63 points BP1	13
		Buildup	BMT 63 points BP1	42

The first and the second interference tests were both carried out with borehole V1 as the source hole. Figure 8.14 shows the test layout for these two tests. The pressure responses in borehole V2 as a function of time were evaluated assuming radial flow and homogeneous and double-porosity system respectively, c.f. Figure 8.15. In the latter assumption, the pressure response depends not only on the fracture/matrix hydraulic conductivity ratio, but also on the storativity ratio. The greater the ratio of storativities, the earlier is the time of transitional curve deviation. This deviation and the initial shape of the response curve basically affect the interpretation of the interference test. Type-curves for different ratio of the storativities presented by Streltsova (1983) are shown in Figure 8.16.

The results from the interpretation using these curves and using the conventional Theis curve for homogenous

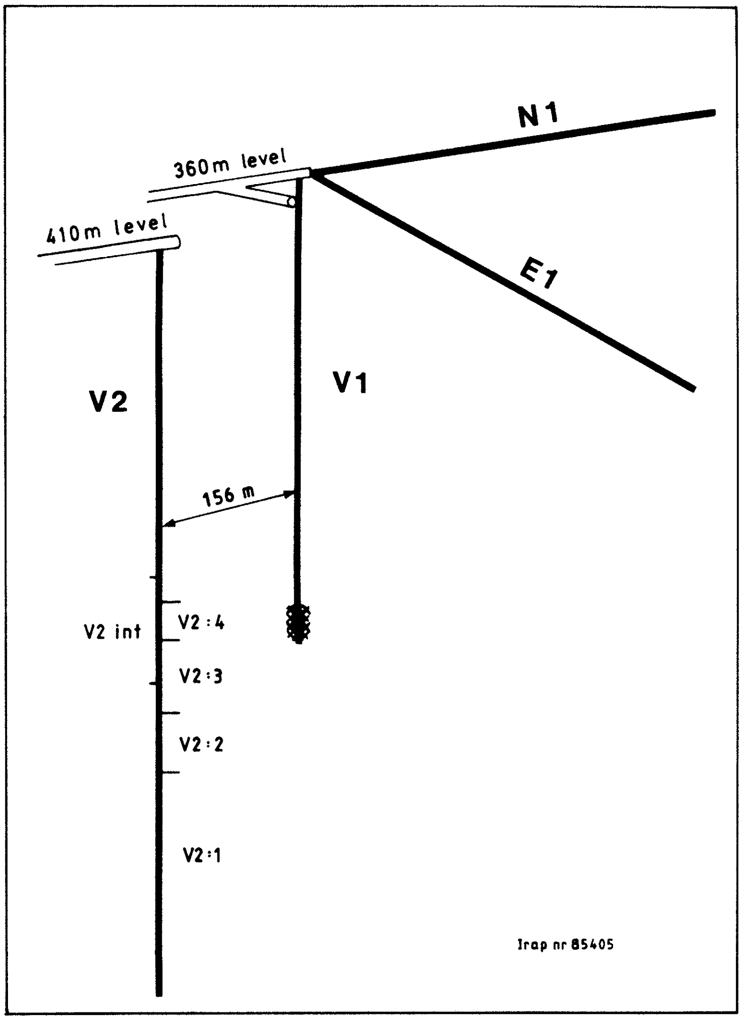

Figure 8.14. Test layout for interference test no 1 and 2. Source section in the bottom of borehole V1.

and isotropic condition are given in Table 8.3 and 8.4. The transmissivity values obtained are 4-10 times lower for the double-porosity system approach compared to the homogeneous system. As regards the storage coefficient the same comparison shows 100-1200 times lower values.

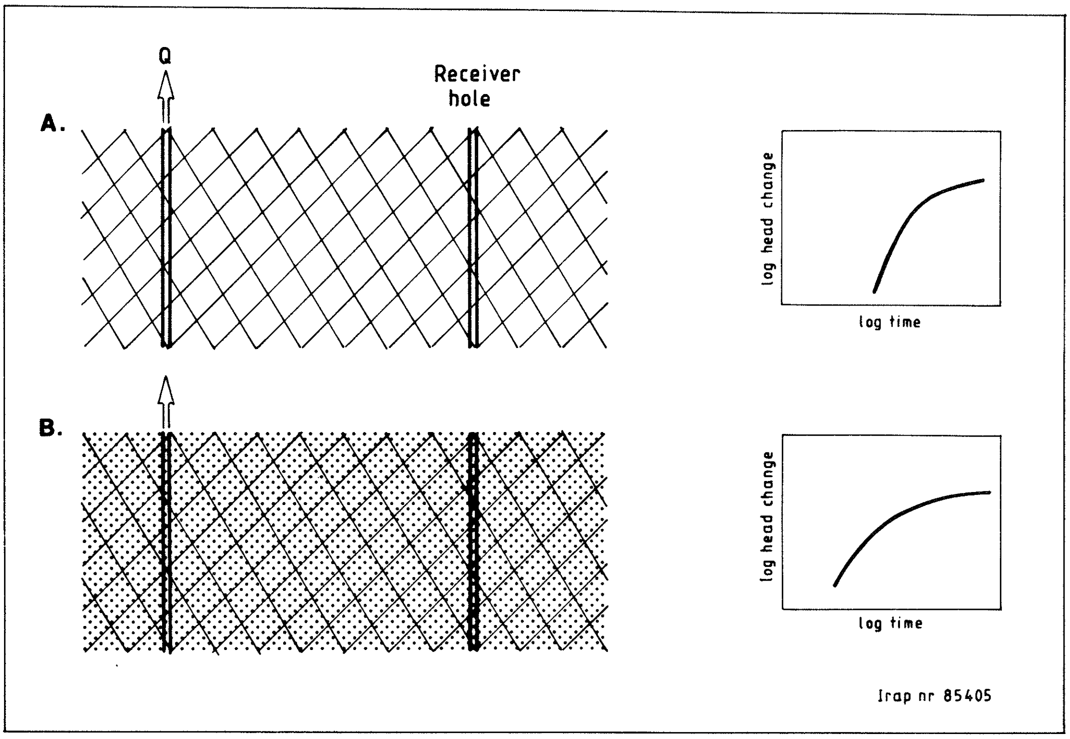

Figure 8.15. The concepts of homogeneous equivalent porous (A) and double-porosity media (B) and the theoretical responses in head change versus time in interference tests.

Table 8.3. Values on transmissivity and storage coefficient obtained from interference tests no 1 and 2 by interpretation according to Theis.

Receiver section	Distance to source sec.	T m^2/s	S
V2:1	307 m	$1.5\ 10^{-6}$	$4.2\ 10^{-5}$
V2:2	185 m	$8.5\ 10^{-7}$	$5.7\ 10^{-5}$
V2:3	157 m	$8.3\ 10^{-7}$	$7.2\ 10^{-5}$
V2:4	155 m	$9.8\ 10^{-7}$	$6.6\ 10^{-5}$
V2-int	156 m	$3.6\ 10^{-6}$	$3.2\ 10^{-5}$

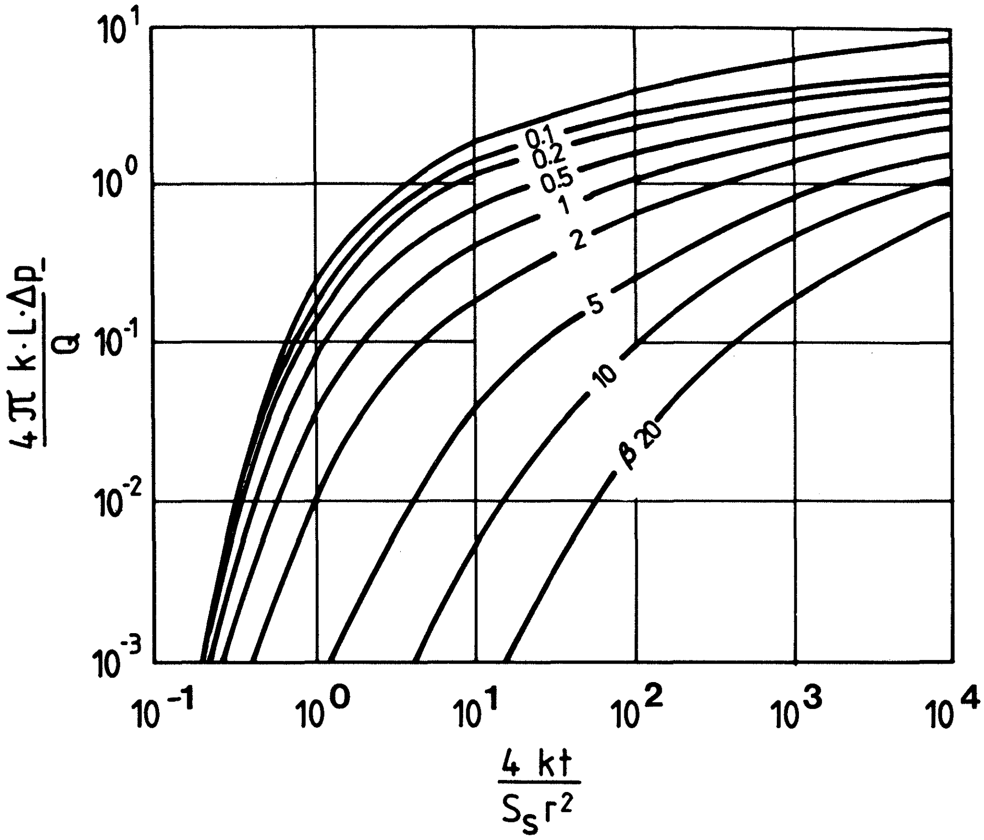

Figure 8.16. Type curves for analysing interference tests according to Streltsova (1983).

Table 8.4. Values on transmissivity and storage coefficient obtained from interference tests no 1 and 2 interpreted according to Streltsova (double-porosity model).

Receiver section	Distance to source sec.	T m^2/s	S
V2:1	307 m	$1.6\ 10^{-7}$	$3.4\ 10^{-8}$
V2:2	185 m	$1.6\ 10^{-7}$	$2.0\ 10^{-7}$
V2:3	157 m	$2.0\ 10^{-7}$	$2.0\ 10^{-7}$
V2:4	155 m	$2.5\ 10^{-7}$	$6.6\ 10^{-7}$
V2-int	156 m	$5.8\ 10^{-7}$	$3.3\ 10^{-8}$

8.7. Practical aspects on underground testing

Investigation of hydraulic properties and conditions at a repository site during construction will include frequent use of underground hydraulic testing. In these types of tests, the hydraulic head in the test sections will always be higher than the actual test site when the work takes place below the groundwater table. Such conditions require that special considerations should be taken to equipment, test design and test performance.

When making a borehole, horizontally or vertically, from an underground drift or shaft, groundwater will be drained by the borehole. This drainage will influence the head around the hole. A hydraulic test performed later in such a borehole or section of the borehole will then be influenced by the borehole history, i.e. its change in head and flow during the time preceeding the test. Thus after drilling a borehole underground for hydraulic testing, it is recommended to seal the borehole by a packer system or at least by a packer situated some meters into the borehole. This will reduce the drainage of the rock around the borehole and the large head decline which otherwise may develope.

The testing procedure in a single borehole starts by introducing the test equipment into the borehole. This should be done with the shortest time available for the borehole to be open. The equipment for build-up testing of selected sections should consist of at least three packers. The uppermost packer should be sited 10-20 meters above the first packer for the test section. By such an arrangement, the hydraulic gradient along the borehole over the test section will be reduced and the influence on the test by this gradient minimized. Test equipment where the test section can be moved without having to open the upper packer will be very useful and promising equipment. In this case the uppermost packer is stationary at the beginning of the borehole.

Single hole hydraulic tests can be used in two ways; to obtain complete information on the hydraulic conductivity and head distribution in sections along the borehole or to obtain detailed information on preselected sections of presumed increased hydraulic conductivity or continuous fractures. The second use requires that the sections to be tested have been selected from other investigations or from a hydraulic conductivity logging of the borehole. When performing a conductivity logging of a borehole from an underground site, the time for each test has to be limited. However, the shorter the test, the less is the volume of the tested rock. In the Swedish program for hydraulic testing from the ground surface, transient testing with constant injection head is used. The testing time of two hours injection and two hours of recovery will give as an average 1.5-2 sections tested per day. Shorter test time and the use of pseudo-stationary interpretation technique may reduce the total time for each test. In the current program, the transient constant head injection tests were applied but due to the natural formation pressure transience and the testing limits of the equipment used, these tests could only be performed under conditions where this transience was very slow. Better equipment with the use of an additional packer would have improved the situation.

Build-up tests require a flowing time of about three times the build-up time before shut-in. The build-up time is also influenced by the wellbore storage which requires a long test time for the interpretation. The build-up tests could be used in hydraulic logging of a borehole. However with the different requirements set up it is no faster testing method than the injection method. There are, however, some advantages. No foreign water is introduced into the borehole, no pumps are required and no excess pressure is applied in the borehole. The build-up tests require a good knowledge of the water head in the test section and that a valve is available close to the test section to exclude a long connection line of water to the test section during the testing sequence. At the test site there is a limited amount of supporting equipment needed; no water storage, pumps etc.

8.8. Reliability of different testing and evaluation techniques

As described in the previous sections, the most pronounced influence on the results is the natural formation pressure transience. This transience will occur regardless of testing technique applied.

The equipment used for the hydraulic testing is not totally incompressible. Even a slight compressibility will be of significance when testing in formations of very low hydraulic conductivity. However, to reduce the influence of the equipment compressibility, testing using constant pressure in the test section is recommended. In this type of testing, the injection flow rate is monitored as a function of time. In the interpretation technique the graph of one over flow rate versus log of time is used and the well-function for constant head is approximated by the log-function according to Jacob and Lohman (1952). This approximation is valid for test times longer than 6 minutes when $K > 10^{-12}$ m/s and the specific storage coefficient is about 10^{-8} 1/m. For higher values of the hydraulic conductivity, the required test time limit is shorter. Thus, the interpretation made according to the approximation by Jacob and Lohman is valid for the injection tests currently performed.

Due to the limited testing time during the injection phase (2 hours), it is not possible to identify the behaviour of a double-porosity system. The very first data on the flow rate are uncertain due to difficulties of rapid registration and large changes in the rate.

Thus, the straight line in the semilog graph may indicate the intermediate flow regime in a double-porosity system behaviour. In those cases the value of the hydraulic conductivity is overestimated by a factor of two.

The evaluation of hydraulic conductivity using the recovery period after a constant head injection phase may be influenced by:

- The length of the injection period
- Wellbore storage and skin

In the case of no wellbore storage or skin, a correct straight line will occur in a Horner graph for shut-in times t′ given by:

$$t' > 40\ r_w^2 S_s / K \qquad (8\text{-}2)$$

provided that the injection time t is fullfilled by:

$$t > 1000\ r_w^2 S_s / K \qquad (8\text{-}3)$$

The requirement set by Eq (8-3) is illustrated in Figure 8.17 for a specific storage coefficient of 10^{-8} 1/m. According to the figure, hydraulic conductivity values higher than 2 10^{-12} m/s are possible to evaluate from the recovery period when the preceding injection period is two hours. This is also illustrated by the graph of conductivity values from injection and recovery periods, where a good correlation between the values is obtained down to 10^{-11} m/s, c.f. Figure 8.18. Thus the reliability of the hydraulic conductivity values obtained from recovery test are not good for values below 2 10^{-12} - 10^{-11} m/s.

When wellbore storage is present, the time t′ needed to reach the correct straight line can be expressed as (Uraiet and Raghavan 1980):

$$t' > 9.34\ 10^3\ C/K \qquad (\text{sec}) \qquad (8\text{-}4)$$

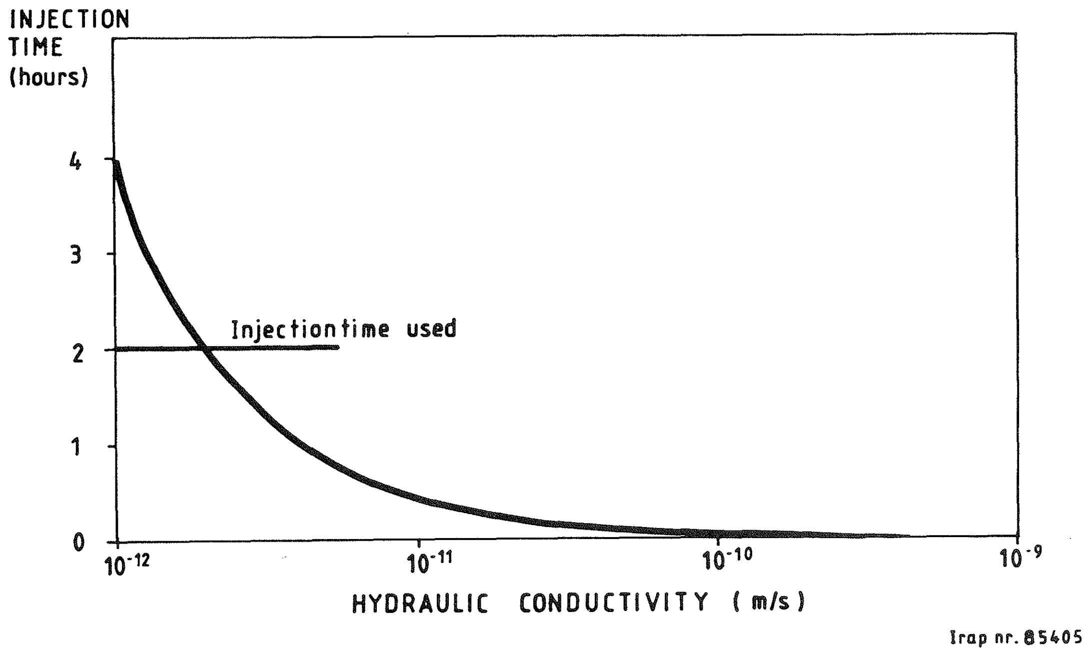

Figure 8.17. The relation between injection time required and hydraulic conductivity for estimating the hydraulic conductivity from the recovery period assuming no wellbore storage. Specific storage coefficient is set to 10^{-8} 1/m.

where C is the wellbore storage coefficient. Assuming an average wellbore storage coefficient of 3 10^{-11} m^3/Pa, the relation between required time and hydraulic conductivity will then be given by the diagram in Figure 8.19. Thus the recovery curves could only be used for hydraulic conductivity higher than 4 10^{-11} m/s when wellbore storage affects the results. This is a requirement which will strongly limit the use of recove-

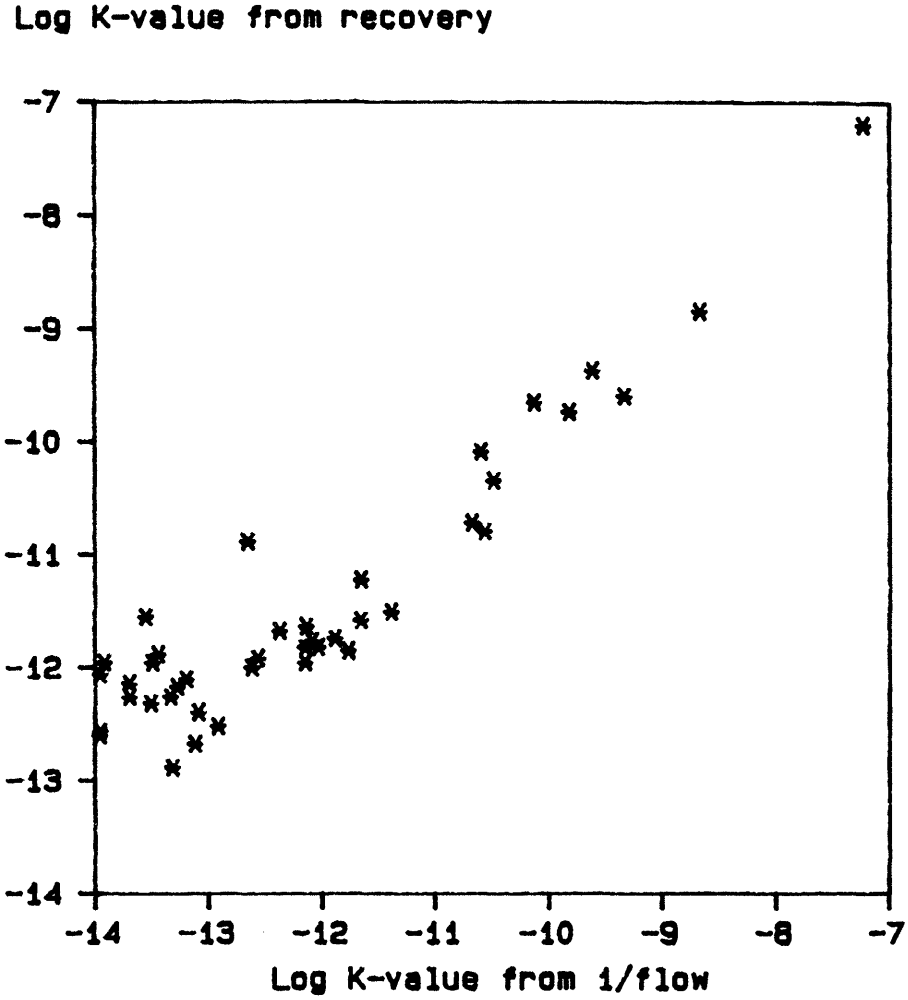

Figure 8.18. Comparison between hydraulic conductivity obtained from injection and recovery stages respectively.

ry data for interpretation of hydraulic conductivity.

The same discussion as to the recovery testing can be said for the build-up tests performed. However these tests have been carried out during a longer time period and the requirements set up by the effects of wellbore storage and skin are usually met.

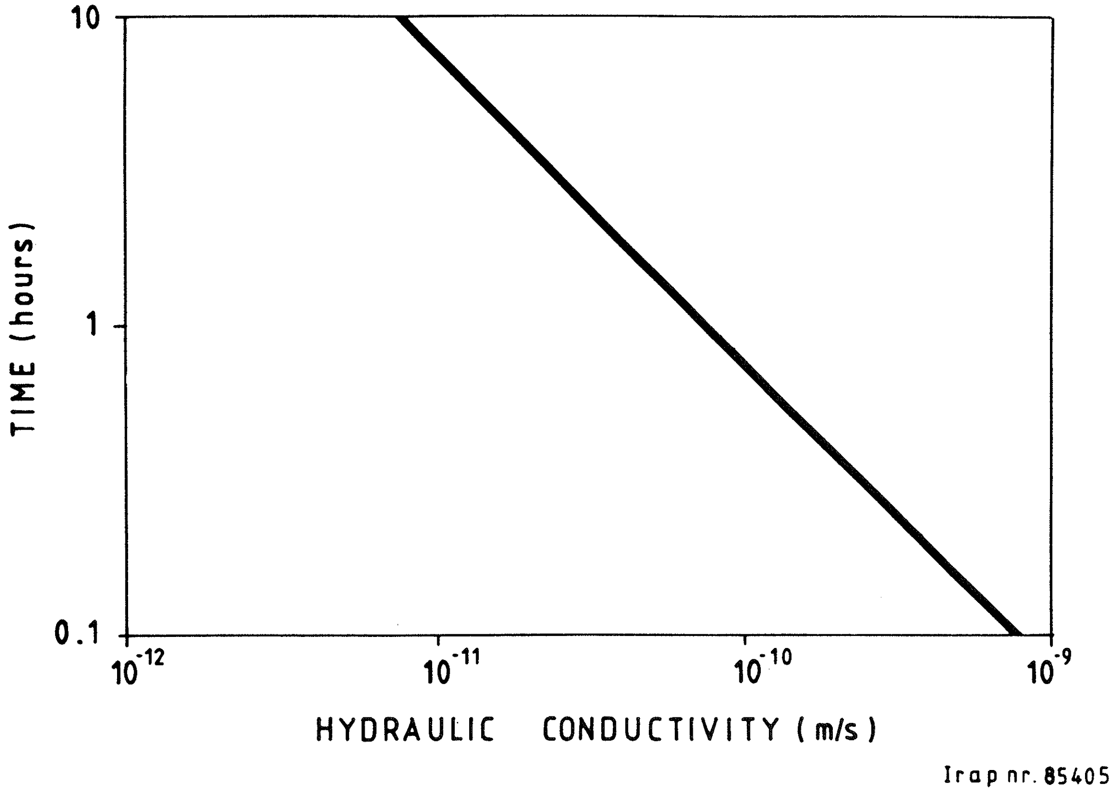

Figure 8.19. Required injection time prior to recovery test versus hydraulic conductivity. Wellbore storage coefficient is set to $3 \cdot 10^{-11}$ m^3/Pa.

9. MODELING

A rough model calculation was carried out in order to investigate the reliability of the obtained results on a large scale. The borehole testing gives values which are valid for the immediate vicinity of the test section. In order to determine the groundwater flow on a regional scale individual test results must be averaged in a way that they reflect the actual hydraulic conductivity in the very same scale. At the present, the model results are calibrated against the inflow to the mine which actually reflects the water bearing ability of the rock mass on a large scale (Carlsson et al, 1983b).

The calculations were based on available data on the hydraulic conductivity and water heads. Far from the mine the water head is assumed to be a function of the topographical conditions, which is the usual pattern in the Swedish crystalline bedrock. The groundwater level is closely bound to the ground surface, a consequence of the low hydraulic conductivity in the geological formations in combination with a humid climate. It is only in very highly conductive or drained formations that the groundwater level is situated at lower levels than 2 m below the ground surface.

The model calculations made were performed for a vertical plane laid out from the center of Lake Rosvalen through the mine and further on about 4 km towards NNW. In total the section was 7 km in length and 2.6 km in depth. The mine was simulated as two horizontal drifts each 1000 m in length at the levels 410 m and 290 m respectively, which gives a drainage threshold which fairly well corresponds to the actual conditions at Stripa.

The calculations were carried out using a finite-element program and assuming two-dimensional flow at steady state, which also are conditions that are well fulfilled at Stripa. The lower and vertical boundaries of the studied plane were set as no flow boundaries. The groundwater

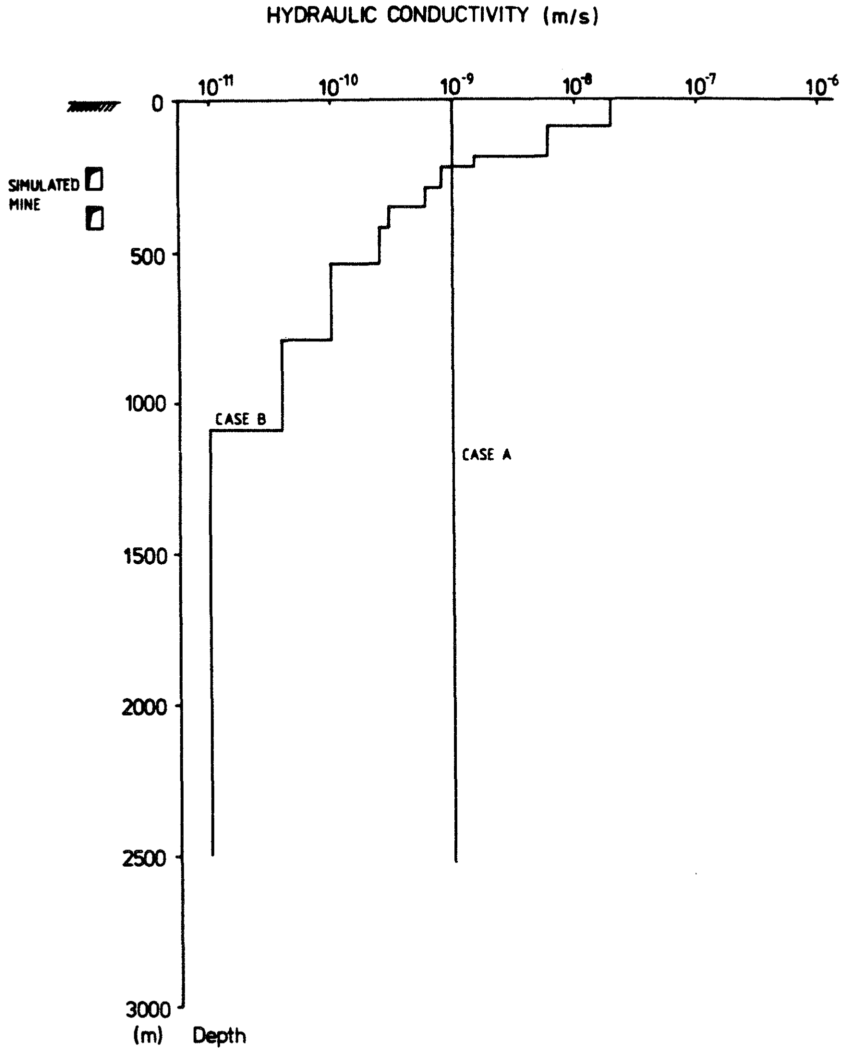

Figure 9.1. Hydraulic conductivity versus depth used in the model calculations.

head at the upper boundary was given as the ground surface. At the mine, the head was set at datum level.

As a result of the calculations, the head distribution was obtained together with the inflow to the mine. The calculations were performed in a vertical plane and the total inflow to the mine was estimated by assuming an equal inflow per m along the drifts. Thus no account was taken of the three dimensional effect at the ends of the simulated drift, which leads to a minor underestimation of the total inflow.

The hydraulic conductivity of the rock mass was given different values to illustrate different possible conditions in the rock mass. Two major types of conductivity

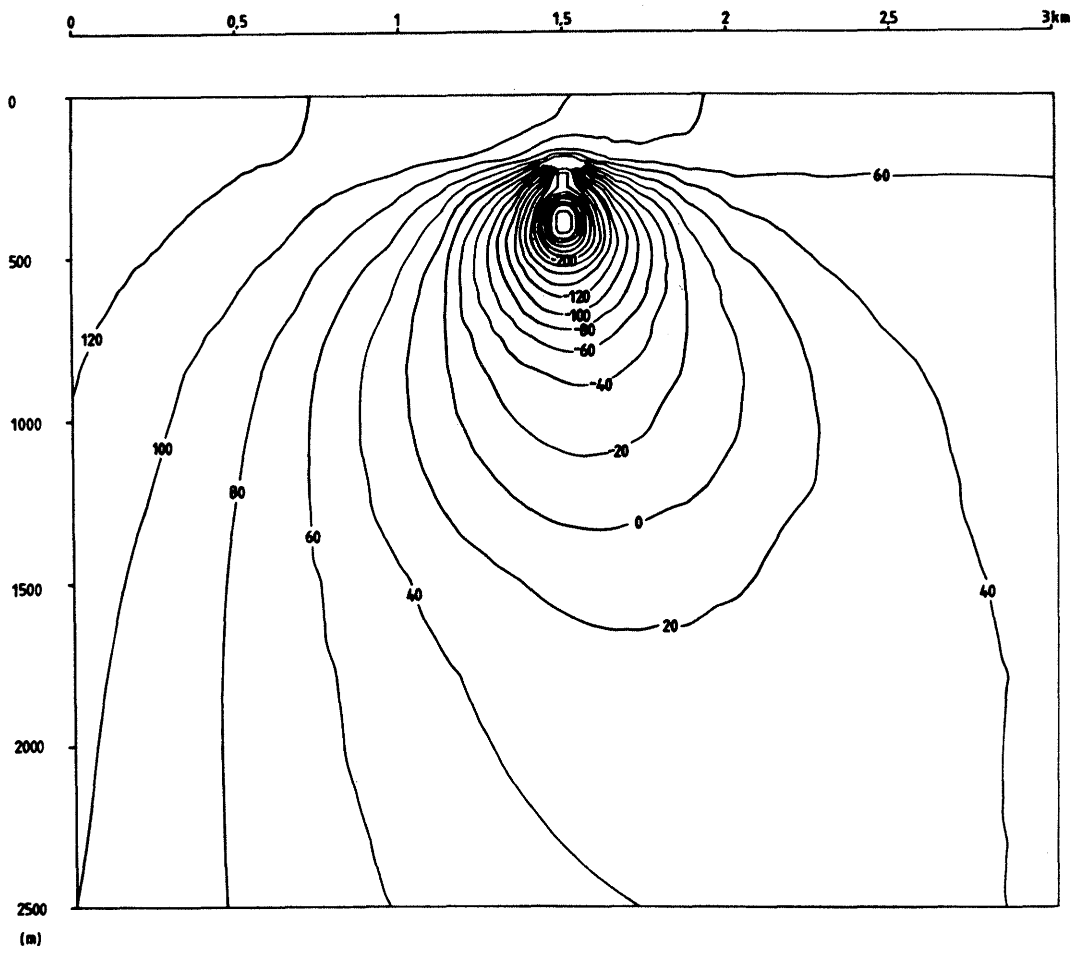

Figure 9.2 Groundwater head around the mine calculated with the numerical model, Case B.

distribution versus depth were used, one with a constant conductivity independent of the depth, and one with a decreasing conductivity versus depth. The first approach is then represented by an overall average as it occurrs at the 360 m level of the mine, and the second is more adapted to the actual conditions as they occur from the tests at different levels, from the surface down to the deeper parts of the tested rock mass. The applied conductivity distributions are presented in Figure 9.1.

The result of the calculations are presented in Figure 9.2 as groundwater head in the vicinity of the mine. The result is in good agreement with the results obtained from the water head measurements as given above in section 2. Table 9.1 summarizes the results in terms of distance of influence of the mine drainage and as total inflow to the simulated mine. The actual inflow to the mine amounts to about 470 l/min as an average inflow over the period January 1983 - December 1984. This value includes direct surface inflow via open mine systems. The groundwater is thus lower than the recorded value.

The result from the calculation based on the decreasing conductivity case (case B) gives a more reliable result as it is based on the actual, measured, conductivity profile in the Stripa granite. The obtained, much lower inflow compared to the actual inflow, is a consequence of the fact that single individual fracture zones carry great weight on the inflow; the water yielding capacity of the zone in V1 amounts to about 10 per cent of the total inflow to the mine, and thus, only a few zones of this character should explain the differences between the calculated and actual inflow. The existence of such zones in the leptite part of the mined areas is not investigated. The conductivity profile versus depth does not take this kind of water-bearing fracture zones into account. These zones, as the V1 zone, are therefore probably the cause of the major part of the actual discrepancy in inflow.

The interference tests made in the mine show that the fractured zones may be hydraulically connected over great distances. The test results show that there is a clear interconnection between borehole V1 and V2 and between N1 and the BMT-area. This indicates that several zones of higher conductivity may exist in the granite area.

Table 9.1 Results of the numerical calculations of the distance of influence and the groundwater inflow to the Stripa mine.

Assumptions made regarding the K-value of the rock mass	Horizontal distance for 50 m influence at the mine level 400 m in km	Groundwater inflow to the mine in l/min
Case A. Homogen. condition with $K=1.10^{-9}$ m/s	0.8	73
Case B. Decreasing K-value from 2.10^{-8} down to $3. 10^{-11}$ m/s	0.45	96

10. CONCLUSIONS

The different activities included in the current program have each provided valuable insight in the applicability, reliability and the advantages of different techniques applied. Together the activities have been used to achieve a sound program for hydrogeological, geological and geophysical testing of boreholes drilled from an underground site. As a supplement, data on the Stripa site have been obtained, and thus, increasing the huge stock of data and the understanding of an underground site in a crystalline plutonic rock.

From the drilling and core-logging procedure, the following conclusions are obtained:

- Drilling of subhorizontal boreholes of 300 m length can be carried out without any difficulties involved. Longer borehole could certainly be achieved without any anticipated problems.

- Drilling deviations for horizontal boreholes of 300 m length are small. In the vertical direction about one meter of deviation was obtained and in horizontal direction almost nine meters.

- Total drilling cost is less for small diameter (56 mm) compared to large diameter (76 mm).

- The core-logging procedure should be as detailed as possible, and the data computerized for further treatment on a statistical basis.

- Orientation of cores should be performed and an improved technique which also is applicable in vertical borehole should be developed.

The rock stress measurements performed have given a three-dimensional picture of the stress field. The technique of over-coring is a very promising method.

The standard geophysical borehole logging program applied has given valuable information on the penetrated bedrock. However, no single log will give a complete picture of the bedrock and an integrated logging program is necessary. For geological and hydrogeological descriptions the following logs gave the most vauable information:

- natural gamma log
- point resistance log
- resistivity logs
- temperature and resistivity logs of the borehole fluid

Other logs not used in the program, as neutron-neutron, gamma-gamma and tube wave seismics, would certainly have improved the knowledge of the penetrated bedrock. A combination of geological, geophysical and hydraulic logging methods will so far give the most integrated knowledge of a penetrated rock mass.

In the current program only the Mise a la masse method was used for geophysical cross-hole investigation. Due to its simplicity it could easily be performed, but however, the information gained had to be compared to a large body of possible models, which usually resulted in more than one possible explanation to the measured set of data. An improved use of non-destructing cross-hole techniques for geometrical mapping of fractures and fracture zones is recommended for further studies.

An underground site will influence the groundwater head distribution around the site and create a high hydraulic gradient out in the bedrock. When the head distribution is measured in boreholes drilled from the site, care has to be taken to this gradient. In order to avoid large gradients along the boreholes, a straddle-packer system should be used. Groundwater head should further be monitored in sections with increased hydraulic conductivity and the measurements should include limited section length.

The hydraulic testing performed have utilized the hydraulic conditions created by the underground site. The shut-in tests performed have called for a very careful evaluation procedure. They are also rather time consuming when sections of very low hydraulic conductivity are considered. Great care should be taken to the borehole history when performing and evaluating the shut-in tests. In order to obtain an accurate interpretation of the data, due considerations should be taken to wellbore and skin.

The injection-recovery tests performed are a faster technique than the shut-in tests. However, the requirement of stable head conditions in the test section before the testing, calls for a long stabilization period. This method also requires an equipment which can withstand high pressure during the injection period. If the requirements of stable head conditions are not met, the tests are difficult to evaluate.

Hydraulic interference tests could preferably be carried out using the natural hydraulic situation around an underground site. The tests will mainly be applied to sections of high hydraulic conductivity to locate connections between zones in different boreholes and to get values of directional hydraulic conductivity over large distances. In the evaluation process, care should be taken to the double-porosity behaviour of the fractured formation.

In general, the shut-in tests give more accurate results as it is possible to obtain additional information on the hydraulic properties due to the long test time. On the other hand, this technique is very time consuming and should therefore only be regarded when special information is required. For an underground testing program in a potential repository site, different demands are to be fulfilled, and the most efficient way to obtain the proper information will be to combine different techniques which cover different degrees of accurracy, geometry and scale.

The data obtained during the current program on the geological and hydrogeological setting of the Stripa site have shown that large fracture zone can be unexpectedly encountered e.g. the bottom of borehole V1. When such a zone is encountered, efforts have to be put in to describe its geometry and properties, in order to evaluate its relative importance to safety assessment for the repository.

11. REFERENCES

Agarwal,R.G., Al-Hussainy, R., and Ramey Jr, H.J.,1970: An investigation of wellbore stotage and skin effect in unsteady liquid flow: I. Analytical treatment. - Soc. Pet. Eng. J. Sept 1970, pp 84-95.

Almen, K., Hansson, K., Johansson, B-E., Nilsson, G., Andersson, O., Wikberg, P., and Åhagen, H., 1983: Final disposal of spent nuclear fuel - Equipment for site characterization. - SKBF/KBS Technical Report 83-44, 55 pp.

Carlsson, H., Carlsson, L., Jämtlid, A., Nordlander, H., Olsson, O., Olsson, T. 1983a: Cross-hole techniques in a deep seated rock mass. - Bulletin of the International Association of Engineering Geology, No 26-27, pp 377-384, Paris 1983.

Carlsson, L., and Olsson, T. 1981: Hydrogeological investigations in boreholes. Summary of defined programs. - Stripa Project. Technical Report 81-01.

Carlsson, L., and Olsson, T., 1985: Hydrogeological investigations in boreholes. Hydraulic testing part 1. Shut-in tests. - Stripa Project. In press.

Carlsson, L., and Olsson, T., 1985: Hydrogeological investigations in boreholes. Hydraulic testing part 2. Injection-recovery tests and interference tests. - Stripa Project. In press.

Carlsson, L., Norlander, H., and Olsson, T., 1983b: Hydro-geological investigations in boreholes. - OECD/-NEA Workshop on Geological disposal of radioactive waste. In Situ Experiments in Granite, pp. 109-120.

Carlsson, L., Egerth, T., Olsson, T., and Westlund, B., 1982a: Core-logs of the vertical borehole V2. - Stripa Project, Internal Report 82-05.

Carlsson, L., Olsson, T., and Stejskal, V., 1981: Core-logs of borehole V1 down to 505 m. - Stripa Project, Internal Report 81-05.

Carlsson, L., Olsson, T., and Stejskal, V., 1982b: Core-logs of the subhorizontal boreholes N1 and E1. - Stripa Project, Internal Report 82-04.

Carlsten, S., 1985: Hydrogeological investigations in boreholes. Geology. - Stripa Project. In press.

Gale, J.E., 1982: Hydrogeologic characteristics of the Stripa site. - University of Waterloo, Report 003C.

Garcia-Rivera, J., and Raghavan, R., 1979: Analyses of short-time pressure data dominated by wellbore storage and skin. - Soc. Pet. Eng. J., pp 106-114.

Hiltscher,R., Martna, J. and Strindell, L., 1979: The measurement of triaxial rock stresses in deep boreholes and the use of rock stress measurementsnin the design and construction of rock openings. - 4th Int. Congr. in Rock Mech., 2, pp. 227-234. Montreux.

Jacob, C.E., Lohman, S. 1952: Nonsteady flow to a well of constant drawdown in an extensive aquifer. - Trans. Am. Geophys. Union, Vol 33, no. 4.

Jacobsson, L., Norlander, H. 1981: Equipment for hydraulic testing. - Stripa Project, Internal Report 81-04.

Koark, H.J., Lundström, I. 1979: Geological map of bedroc, Lindesberg SW. - Swedish Geological Survey, Ser Af 126. Uppsala. (In Swedish).

Leeman, E.R., and Hayes, D.I., 1966: A technique fordetermining the complete state of stress in rock using a single borehole. - First Int. Congr. on Rock Mech., 2, pp. 17-24. Lisboa.

Lindblom, S.: Hydrogeological and hydrogeochemical investigations in boreholes - Fluid inclusion studies in the Stripa Granite. - Stripa project Internal Report 84-07.

Magnusson, K-Å., and Duran, G., 1984: Comparative study of geological, hydrological and geophysical borehole investigations. - SKB/KBS Technical report 84-09.

Moye, D.G., 1967: Diamond drilling for foundation exploration. - Civ. Eng. Trans. CE9, pp.95-100.

Olkiewicz, A., Gale, J.E., Thorpe, R., Paulsson, B. 1979: Geology and fracture system at Stripa. - SAC Report 21.

Olkiewicz, A., Hansson, K., Almen, K-E, Gidlund, G. 1978: Geological and hydrogeological basic documentation of the Stripa test station. - SKBF/KBS Technical Report 63. (In Swedish).

Olsson, O. and Jämtlid, A.: Hydrogeologcal and hydrogeochemical investigations - Geophysical borehole measurements. - Stripa Project Internal report 84-03.

Raghavan, R. 1976: Some Practical Considerations in the Analysis of Pressure Data. - Jour. of Pet. Tech. Oct 1976, pp 1256-1268.

Raghavan, R., 1980: The effect of producing time on type curve analysis. - J. Pet. Tech., June 1980, pp. 1053-1064.

Strelsova, T.D., 1983: Well pressure behaviour of a naturally fractured aquifer. - Soc. Pet. Eng. J., Oct 1983, pp. 769-780.

Strindell, L., and Andersson, M.: Measurements of triaxial rock stresses in borehole V1. - Stripa Project Internal report 81-05.

Uriaet, A.A., and Raghavan, R., 1980: Unsteady flow to a well producing at constant pressure. - J. Pet. Tech., Oct. 1980, pp.1803-1812.

Wilson, C.R., Long, J.C.S., Galbraith, R.M., Karasaki, K., Endo, H.K., DuBois, A.O., McPherson, M.J., Ramqvist, G. 1981: Geohydrological data from the macropermeability experiment at Stripa, Sweden. - SAC report 37.

Wollenberg, H., Flexser, S., Andersson, L. 1980: Petrology and radiogeology of the Stripa pluton. - SAC Report 36.