TECHNICAL REPORT

90-41

Groundwater in crystalline bedrock

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BERGAB – Berggeologiska Undersökningar AB

June 1990

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Information on SKB technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17), 1982 (TR 82-28), 1983 (TR 83-77), 1984 (TR 85-01), 1985 (TR 85-20), 1986 (TR 86-31), 1987 (TR 87-33), 1988 (TR 88-32) and 1989 (TR 89-40) is available through SKB.

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ABSTRACT

The aim of this project was to make detailed descriptions of the geological conditions and the different kinds of leakage in some tunnels in Sweden, to be able to describe the presence of ground water in crystalline bedrock. The studies were carried out in TBM tunnels as well as in conventionally drilled and blasted tunnels. Thanks to this, it has been possible to compare the pattern and appearance of ground water leakage in TBM tunnels and in blasted tunnels. The extent to which the differences are attributable to disturbed leakage patterns because of increased fracturing and opening of old fractures through the blasting process is discussed.

On the basis of some experiments in a TBM tunnel, it has been confirmed that a detailed mapping of leakage gives a good picture of the flow paths and their aquiferous qualities in the bedrock. The same picture is found to apply even in cautious blasted tunnels.

It is shown that the ground water flow paths in crystalline bedrock are usually restricted to small channels along only small parts of the fractures. This is also true for fracture zones. It has also been found that the number of flow paths generally increases with the degree of tectonisation, up to a given point. With further tectonisation the bedrock is more or less crushed which, along with mineral alteration, leaves only a little space left for the formation of water channels. The largest individual flow paths are usually found in fracture zones. The total amount of ground water leakage per m tunnel is also greater in fracture zones than in the bedrock between the fracture zones.

The individual leaks are classified into different types according to appearance, width and aperture. Some of the types are very common and are found in all the tunnels studied, while some types mainly occur in one geological region.

In mapping visible leakage, five classes have been distinguished according to size. Where possible, the individual leak inflow has been measured during the mapping process. The quantification of the leakage classes made in different tunnels are compared, and some quantification standards suggested.

A comparison of leakage in different rock types, tectonic zones, fractures etc is also presented.

TABLE OF CONTENTS

		Page
	ABSTRACT	ii
	SUMMARY AND CONCLUSIONS	v
	FOREWORD	viii
	ACKNOWLEDGEMENTS	ix
1.	INTRODUCTION	1
1.1	BACKGROUND	1
1.2	OBJECTIVES	1
2.	CASE STUDIES - OVERVIEW	2
2.1	INTRODUCTION	2
2.2	OBJECT DESCRIPTIONS	2
3.	METHODS	6
3.1	INTRODUCTION	6
3.2	COMMENTS ON SELECTED PARAMETERS	6
3.2.1	The characteristics of the rock mass	6
3.2.2	Types of fracture patterns	8
3.2.3	Fracture characteristics	10
3.2.4	Fracture fillings	10
3.2.5	Weathering	12
3.2.6	The rock stress conditions	13
3.2.7	Water leakage - fracture volume	13
4.	THE PRESENCE OF WATER IN CRYSTALLINE BEDROCK	15
4.1	BACKGROUND	15
4.2	WATER LEAKAGE - REPRESENTATIVITY	15
4.3	THE AQUIFEROUS PROPERTIES IN DRILL HOLES EXAMINED	18
4.4	LEAKAGE IN DIFFERENT TYPES OF ROCK	18
4.5	LEAKAGE IN DIFFERENT TYPES OF FRACTURES	19
4.6	LEAKAGE IN RELATION TO TYPE AND LENGTH OF FRACTURE	24
4.7	FRACTURE FILLING - AQUIFEROUS PROPERTIES	25
4.8	THE QUALITIES OF THE FRACTURE SURFACE - TYPE OF LEAKAGE	26
4.9	LEAKAGE IN AND NEAR TECTONIC ZONES	26

5. ANALYSIS OF HYDROGEOLOGICAL CONDITIONS 32

5.1 BACKGROUND 32
5.2 QUANTIFICATION OF LEAKAGE 33
5.3 THE AQUIFEROUS QUALITIES OF THE BEDROCK 34
5.4 THE DISTRIBUTION OF WATER IN THE BEDROCK 34
5.5 AQUIFEROUS PROPERTIES OF DIFFERENT ROCK TYPES 36
5.6 AQUIFEROUS QUALITIES IN TECTONIC ZONES 38
5.7 AQUIFEROUS QUALITIES OUTSIDE TECTONIC ZONES 40
5.8 REGIONAL SIMILARITIES AND DIFFERENCES 44

6. HYDROGEOLOGICAL INVESTIGATIONS FOR MODELLING 46
6.1 INTROCUCTION 46
6.2 BASIS FOR MODELLING A SECTION OF BEDROCK 47

REFERENCES 48

SUMMARY AND CONCLUSIONS

This report presents the results of a detailed investigation with the aim of describing the presence of ground water in crystalline bedrock. The investigations were made in tunnels situated in seven different regions in Sweden.

It is found that a detailed mapping of leakages in TBM tunnels and cautious blasted tunnels gives a good picture of the ground water flow paths and their qualities in the bedrock.

The ground water flow paths in crystalline bedrock are usually restricted to small channels along only minor parts of the fractures or along the shear line of two fractures. The number of flow paths and the flow rate in general increase with the degree of tectonisation up to a given point. This is also true in fracture and crush zones, as well as in fracture groups and fracture system. When the bedrock is still more tectonised there is only very small space left for ground water channels. Between the water bearing fractures and fracture zones there may be large sections of rock with no visible ground water.

Fractures along which displacement has taken place usually have more and larger flow paths than other fractures.

Horizontal or subhorizontal fractures or fracture zones may have very large flow paths.

The flow paths form a complex pattern in the bedrock.

The individual leaks have been classified into different types on the basis of appearance, width, aperture, fracture filling, etc. Some of the types are very common and are found in all tunnels. But some types mainly occur in one region.

The individual leaks are also classified according to their estimated inflow. The five classes are "minor drip (v)", "major drip-slowly running water ($\overset{\vee}{\vee}$)", "fast running water-flushing water ($\overset{\vee}{\overset{\vee}{\vee}}$)", "fast flushing water ($\overset{\vee}{\overset{\vee}{\mathbf{\vee}}}$)" and "very fast flushing water ($\overset{\vee}{\overset{\vee}{\overset{\vee}{\vee}}}$)".

In some tunnels, individual leaks have been measured. The quantification of the leakage classes made in different tunnels differs somewhat, but a common standard for the five classes has been established:

v = <0.04 l/min

vv = 0.04 - 0.3 l/min

vvv = 0.3 - 1.5 l/min

vvvv = >1.5 - 6.5 l/min

vvvvv = >6.5 l/min

The tunnels studied represent different geological-tectonic regions. The leakage patterns and thus the patterns of flow paths in the bedrock are very similar for the different tunnels. The largest leaks are found in zones with increased fracturing. Between these zones the leaks are found in individual fractures. In some tunnels no visible leakage is found for long distances. These sections in general appear where the fracture frequency is low.

In the Bolmen tunnel, the largest leak was documented where the tunnel passes trough regional tectonic zones. Semi-regional fracture zones show somewhat less leakage than the regional zones, but considerably more than local fracture zones.

In the Forsmark tunnel tectonic zones account for about 60% of the total leakage. These zones make up about 24% of the total tunnel length. The leakage in the zones is 4.0 l/min,m while the corresponding figure for the rest of the tunnel is 0.8 l/min,m. The leakage in the tectonic zone with the most leakage (8.3 l/min,m) is more than 20 times that in the tectonic zone with the least leakage.

In SFR, about 50% of the leakage is found in the tectonic zones (in spite of grouting). The zones make up about 10% of the total length of tunnels and rock caverns.

In the tunnels in Göteborg and Stockholm the common factor is that the leakage and need for grouting is greatest in zones with increased fracturing. Between the zones, the leakage and need for grouting decreases with decreasing intensity of fracturing.

In the Kymmen tunnel, about 75% of the leakage is found in tectonic zones. The zones make up 15% of the total tunnel length. This means that the tectonic zones have about 17 times more leakages per m than the corresponding figure for the bedrock between the zones.

In the Saltsjö tunnel most of the leakage is found in the tectonic zones. Between these, the leakage pattern is very irregular. More than 50% of the total tunnel length shows no leakage.

The highly detailed mapping in the Stripa tunnel shows that the leakage pattern is very irregular. Leakage occurs in wet sections, with large dry sections in between.

The report also gives quantifications of leakage in different rock types. This is done region for region, to have the same tectonisation of the rock types being compared.

Aquiferous qualities in and outside tectonic zones are described for the different tunnels. Flow rate and qualities are given for leakage of different types. In this way similarities and differences between the tectonic regions are presented and discussed.

FOREWORD

Many countries are considering building repositories for high level nuclear waste at great depths in crystalline bedrock. This crystalline rock is generally more or less fractured and most of the water flow takes place in fractures. Knowledge of the flow paths and their qualities is absolutely necessary for a relevant modelling and analysis of ground water in crystalline bedrock.

This report describes the presence of ground water in Swedish crystalline bedrock. Hopefully the report will contribute to the understanding of water flow in fractured rock and present useful information for modelling work.

ACKNOWLEDGEMENT

The author would like to express his gratitude to Göran Bäckblom, SKB and Ivars Neretnicks, KTH for their positive questioning and discussing of presented descriptions during the production of the report.

1 INTRODUCTION

1.1 BACKGROUND

At the request of SKB, BERGAB-Berggeologiska Undersökningar AB has earlier performed hydrogeological mapping of various tunnels in order to document the presence of water in various geological-tectonic situations. Analysis are presented, in report form, of the correlation between aquiferous properties and different types of rock, fractures, fracture zones, etc.

A pilot project description and classification of fracture zones in crystalline bedrock has also been made.

In order to be able to use the documentation as a basis for modelling and hydraulic calculations, SKB has commissioned BERGAB, upon completion of the compilation and assessment work, to describe the presence of water in the bedrock as documented in various underground constructions. This description also includes comparisons between the conclusions drawn from the documentation carried out, for example, at SFR, Forsmark III and Stripa, and the findings of the studies made at Finnsjön. The documentation at SFR was carried out by Christiansson & Bolvede (1987), and the documentation at Forsmark III by Carlsson & Olsson (1977). The studies at Stripa were carried out by Neretnieks et al (1987) and at Finnsjön by Ahlbom & Tirén (1989).

1.2 OBJECTIVES

The aim of this project is to describe, through analysis of the extensive documentation available, the presence of water in bedrock. One of the underlying intentions is to examine the significance of the rock type, the contact between rock types, and the homogeneity of the rock mass. An important aspect of the analysis is to describe the presence of water in different types of fractures and fracture zones. A further objective is to determine whether fractures and fracture zones may display typical aquiferous qualities in a given region irrespective of the rock type and fracture genesis. Another objective is, as far as possible, to present quantitative information as to the aquiferous qualities of the existing types of fractures and fracture zones, and their distribution.

2. CASE STUDIES - OVERVIEW

2.1 INTRODUCTION

Detailed hydrogeological mapping has been carried out in a large number of bedrock constructions. The statistics on which the analysis presented below is based have been taken primarily from the documentation on the following constructions:

The Bolmen tunnel

The Hylte tunnel

The Kymmen tunnel

The Saltsjö tunnel

SFR

Stripa

The Stockholm subway (Vreten-Sundbyberg)

The Forsmark III tunnel

Tunnels in the Göteborg area

In order to present examples of the presence of water in regional subhorizontal fracture zones, findings from hydrogeological studies carried out at Finnsjö are also included in this report.

2.2 OBJECT DESCRIPTIONS

The locations of the studied objects are presented on figure 2.2.1.

The Bolmen tunnel

The Bolmen tunnel is intended to supply parts of the province of Skåne with fresh water from Lake Bolmen. The tunnel is 80 km long and extends from Lake Bolmen to Perstorp in Skåne. The water will be piped from there to southwestern Skåne. The ground is soil covered along the entire length of the tunnel.

The tunnel area is 8 m^2, a total of just under 2,000 m is included in the hydrogeological study.

1. The Bolmen tunnel
2. The Hylte tunnel
3. Tunnels in the Göteborg area
4. The Kymmen tunnel
5. The Saltsjö tunnel
6. SFR
7. Stripa
8. The Stockholm subway
9. The Forsmark III tunnel

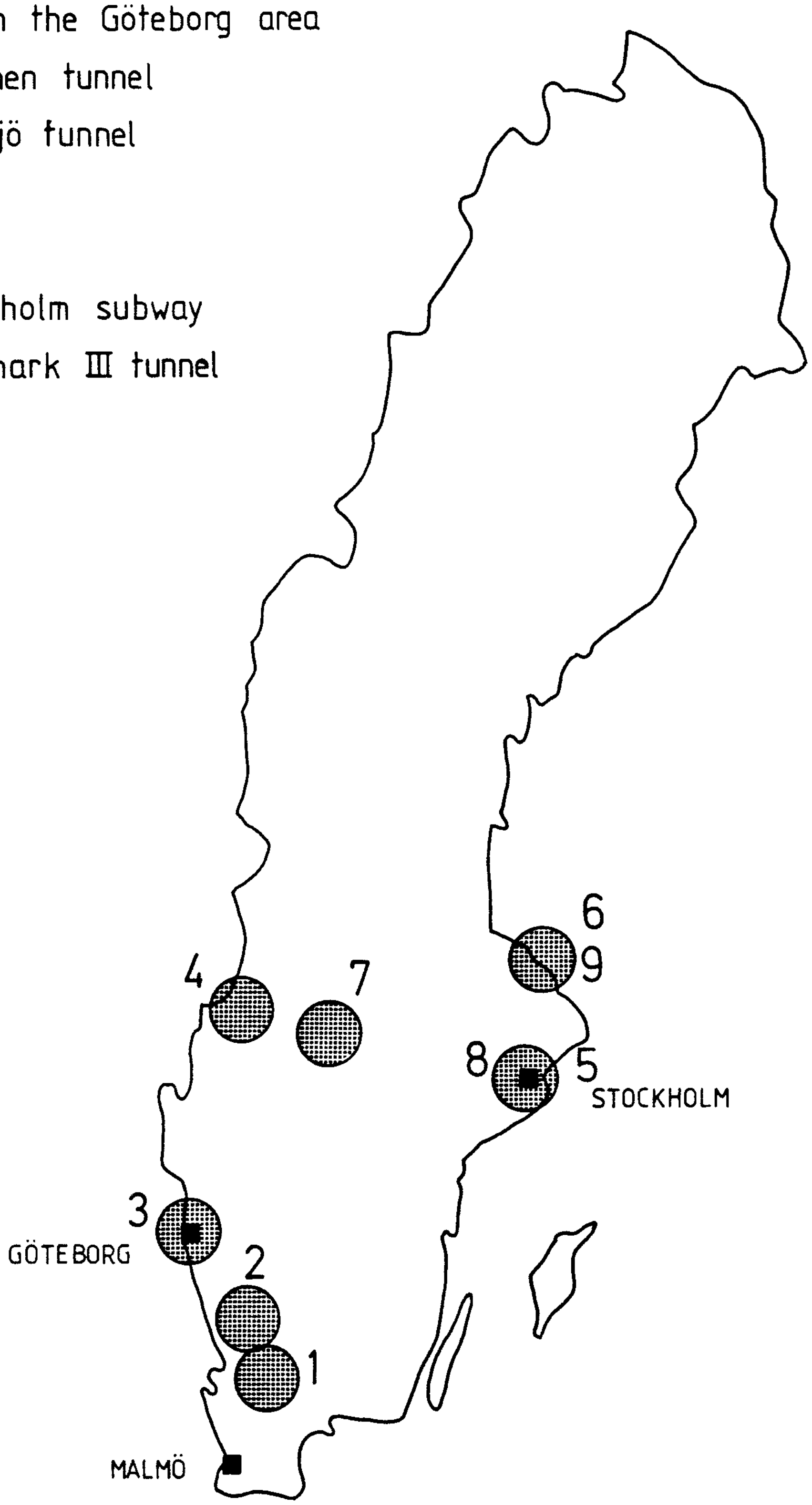


Figure 2.2.1 The location of the studied objects

The Hylte tunnel

The Hylte power station is located in the Nissan river between Hyltebruk and Rydöbruk, about 65 km northeast of the town of Halmstad. The plant includes: a headrace, a raised shaft and V-shaped tunnel crossing under the Nissan river, a dam area, a new power station and a tailrace.

The new power station has been constructed 70 meters below ground level. The vertical drop of the water is 63 meters. The water is conducted out through a 3,550 meter long tail-race with an area of 45 m^2, into the Nissan river near Rydöbruk.

The Kymmen tunnel

The Kymmen power station is located at the north end of Lake Rottnen, approx. 18 km northwest of Sunne in the province of Värmland. The water is conducted from the Rottneälv river and the Granå River to Lake Kymmen through tunnels (approx. 9 km) and then through another 3 km long tunnel down to an under-ground power station at Lake Rottnen.

The hydrogeological mapping has been carried out in the TBM tunnel from the Rottneälv River to the Granå river. The total tunnel length is 5,400 m. 4,527 m of this length was drilled full-face, with an area of 16m^2. The remaining length was conventionally blasted.

The Saltsjö tunnel

The Saltsjö tunnel is a TBM tailrace for water from a heat pump plant in Solna. The tunnel leads into Lake Saltsjö outside Kastellholmen in the Stockholm area, thus passing through an urban area.

The total length of the tunnel is 7.5 km. The section whose hydrogeological conditions have been studied here is 700 m long. This tunnel is approx. 50 - 60 m under ground level, and its diameter is 3.5 m.

SFR

Final storage of low and medium level nuclear waste takes place near Forsmark, along the coastline, approx. 80 meters under sea level. The storage area has been blasted in the bedrock. It is connected with the surface plants on land by two tunnels, each of which is approx 1 km long. SFR will be the final repository for total of approx. 90,000 m^3 of waste.

The facilities comprise the two access tunnels, a silo, rock chambers and connecting tunnels.

Stripa

The Stripa mine is in the mid-Swedish province of Bergslagen, a little less than 20 km north of Lindesberg. The old iron ore mine is approx. 410 m deep. Near it, a test mine has been built in the granite, 360 m under ground level. The test area is a 75 m long tunnel, which is intersected by a 215 m long tunnel. These tunnels are 4.5 m wide, and their abutment height is 2 m.

The Stockholm subway (Vreten-Sundbyberg)

The sections of the Stockholm subway studied here are portions of the southern track section of the Järna line, through Solna and Sundbyberg. The area this line passes through is an urban area. The tunnels are 10 - 15 m under ground level. The rock overburden has been kept as small as possible.

A total of 3,110 m has been mapped. The sections of tunnel studied include both single-track tunnels with an area of 25 m^2, and two-track tunnels with an area of 48 m^2.

The Forsmark III tunnel

The Forsmark tunnel is intended for cooling water and runs from the Forsmark nuclear power plant to an artificial test basin on the island of Loven. The total length of the tunnel is 2,300 m. The section whose hydrogeological conditions have been studied here is 1,921 m long.

The area of the tunnel is approx. 80 m^2. It is located approx. 75 m under sea level with an approximate rock overburden of 55-60 m.

Tunnels in the Göteborg area

Five different tunnels in the Göteborg area have been studied. Four of these are waste water tunnels and the fifth is a district heating tunnel which transfers hot water from the Shell oil refinery on the island of Hisingen to central Göteborg. This tunnel and one of the waste water tunnels pass under urban areas in central Göteborg, while the other three waste water tunnels are located outside Göteborg in less densely-populated areas. The bedrock is partially exposed along these sections.

The hydrogeological study was of approx. 13,900 m of waste water tunnel with an area of 5 m^2, and approx. 900 m of waste water tunnel with an area of 12 m^2. Approx. 3,500 m of the district heating tunnel, with an area of 24 m^2, has also been studied.

3 METHODS

3.1 INTROCUCTION

In order to be able to make a meaningful assessment and description of the presence of water in relation to different geological and tectonic parameters and variations thereof, the parameters concerned must be well defined with regard to their content.

The nomenclature used in this project for description of fracture and crush zones has been in use at BERGAB since 1972 both in the planning of tunnels and rock caverns and in documentation of completed underground constructions.

3.2 COMMENTS ON SELECTED PARAMETERS

3.2.1 The Characteristics of the Rock Mass

Figure 3.2.1.1 is a summary of a number of the most common types of rock in the crystalline bedrock, primarily with regard to the degree of homogeneity and isotropy- anisotropy.

Homogeneous rock mass is mainly composed of one rock type, having identical characteristics in parallel directions. Inhomogeneity in a rock mass increases with increasing presence of different rock types with varying characteristics.

Isotropic rock mass has somewhat similar characteristics in all directions. (There is virtually no rock mass that is wholly isotropic). In an anisotropic rock mass some characteristics (such as structures) dominate in some direction.

Example 1.

Solid granite is basically composed of one single type of rock, and is thus very homogeneous. The mass is subject to very little tectonic influence. The fracture pattern is the usual one for granites, with three directions at almost right angles to one another, thus exhibiting a high degree of isotropy.

Example 2.

A rock mass composed of highly schistose gneiss is homogeneous but ansiotropic.

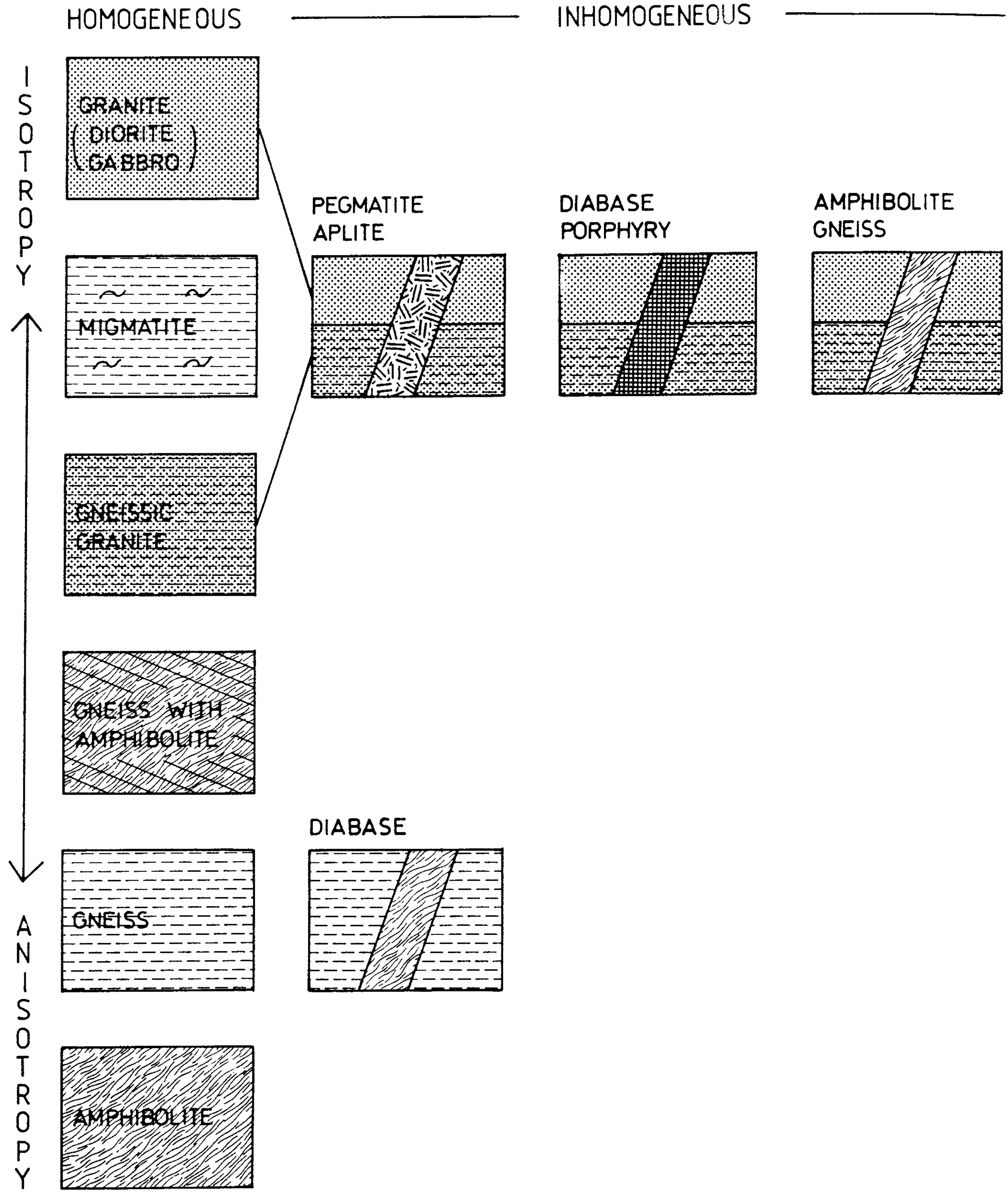


Figure 3.2.1.1 Types of rocks i crystalline bedrock with regard to homogeneity and isotropy

Example 3.

A rock mass composed of gneiss layered with amphibolite is inhomogeneous and anisotropic.

3.2.2 Types of Fracture Patterns

In the parts of the project which have been mapped by BERGAB the fracture patterns in different zones have been registered as well as the fracture patterns in the rock surrounding the zones. Fracture and crush zones are in that connection seen as well defined zones. Fracture-/and crush zones can thus be seen as well defined zones with a clearly increased frequency of fractures in comparison with surrounding rock. When the dominating fractures are parallel with the zones, these zones are defined as fracture zones. Zones are referred to as crush zones when the fracturing in these zones includes several groups of fractures, which causes the rock to be blocky-partly crushed.

Figure 3.2.2.1 describes the basic types of fracture patterns discernable in the surrounding rock and the fracture or crush zones. These types are defined as follows:

Types of fracture patterns outside actual fracture or crush zones:

- "good bedrock" (isolated fractures, no continuous fracturing)
- "fractured bedrock" - generally one fracture group
- "fractured bedrock" - generally two fracture groups delineating blocks of greatly varying sizes
- "large blocky bedrock" - generally three fracture groups, consistently blocky development (block size 60 - 200 cm)

Types of fracture patterns in fracture or crush zones:

- "slaty cleavage" indicates zones in which the bedrock is broken mainly along plane-parallel fractures at intervals $\geq$ 10 cm.
- "thin-slaty cleavage" indicates zones in which the bedrock is brocken mainly along plane-parallel fractures at intervals < 10 cm.
- "blocky rock" indicates zones in which the bedrock is broken mainly along intersecting fracture groups demarcating blocks with edges of 20 - 60 cm.

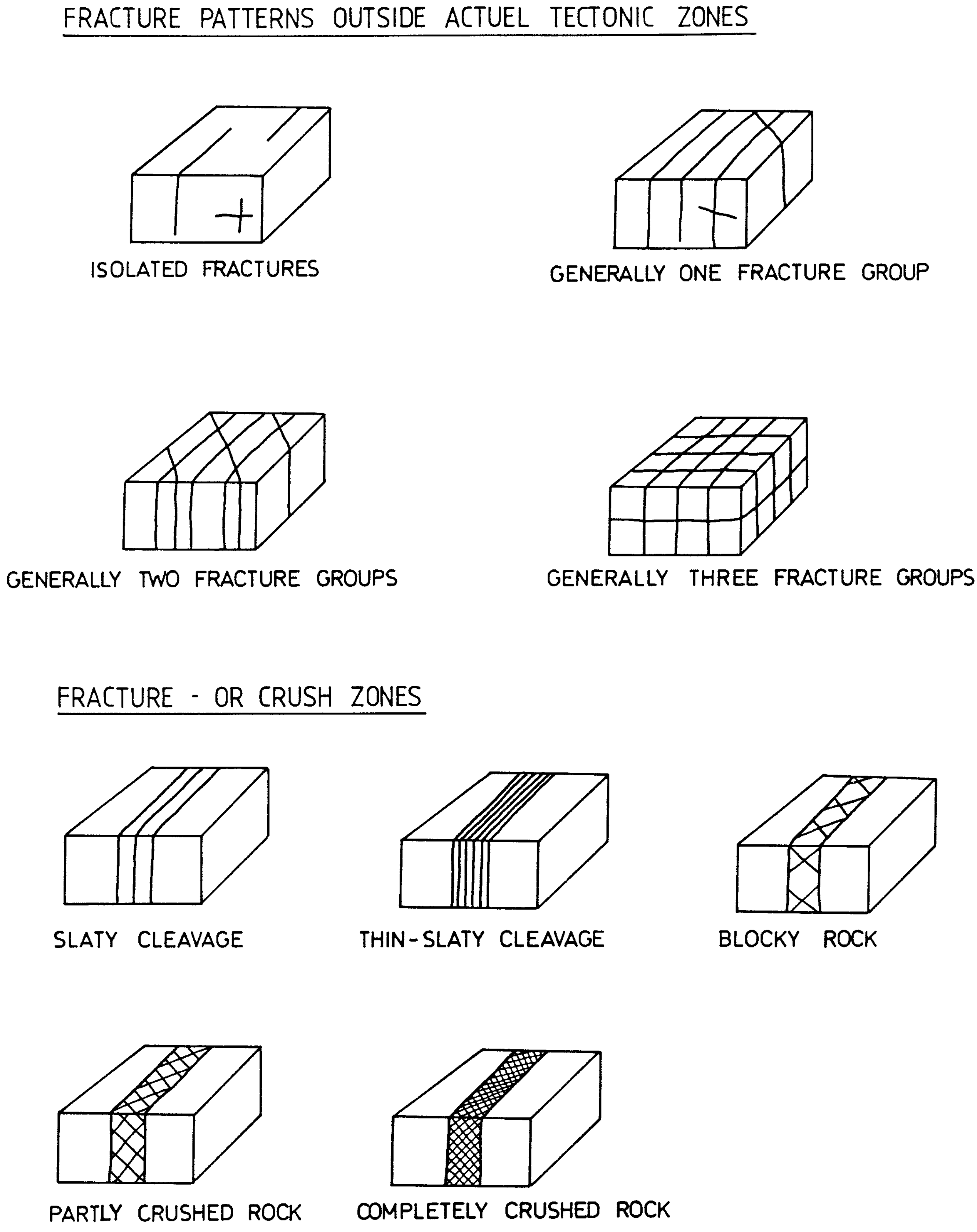


Figure 3.2.2.1 Types of fracture patterns

- "partly crushed rock" indicates zones in which the bedrock is broken mainly along intersecting fracture groups demarcating blocks with edges < 20 cm.

- "completely crushed rock" indicates zones in which the bedrock is entirely fragmented by fractures from intersecting directions.

3.2.3 Fracture characteristics

Normally, fractures belonging to different groups also present different fracture characteristics. In figure 3.2.3.1 examples of fractures with different characteristics are presented. Under stress, bedrock with uneven, rough fracture surfaces, has reacted with ruptural fracturing. No relative movement along the fractures has occurred.

When there was movement along a fracture, there appear either various types of mineral coatings, indicating the direction of movement, or smooth, even surfaces. The mineral coatings often appear as a thin "wallpaper" of mineral alteration covering the fracture surfaces. The different fracture characteristics generally also show different aquiferous properties. In addition to the more or less "open" fractures described above, there are healed fractures in which crystallization, e.g. of quartz or calcite, has completely filled the fractures. With respect to aquiferous properties, these fractures are totally impermeable.

3.2.4 Fracture Fillings

The most commonly occurring fracture fillings in the zones described are chlorite, limonite and clay. This type of fracture filling is generally more or less unconsolidated. In healed fractures fillings which may be found include epodite, calcite, quartz and feldspar (figure 3.2.3.1).

Chlorite is most commonly found in basic bedrock (amphibolite, diabase) where its greenish-black, soapy consistency often functions effectively as a sealant in fractures with even, smooth surfaces. Limonite, as used here, is an umbrella term for a number of common iron oxide hydrates. Limonite is frequently found in conjunction with aquiferous fractures or fracture zones in gneiss bedrock, where it appears as a red, slimy precipitant. Redness along the plane of fractures in core samples indicates water bearing. Limonite is easily washed out of fractures, and thus has a negligible sealing effect.

Clay is an umbrella term used in practice for fine-grained fracture fillings. An extensive amount of material analyzed in clay samples from the Bolmen tunnel and constructions in the Göteborg region indicates that the actual fraction of clay (<2 um) seldom exceed 20%, while the remainder is either silt fractions or coarser fractions.

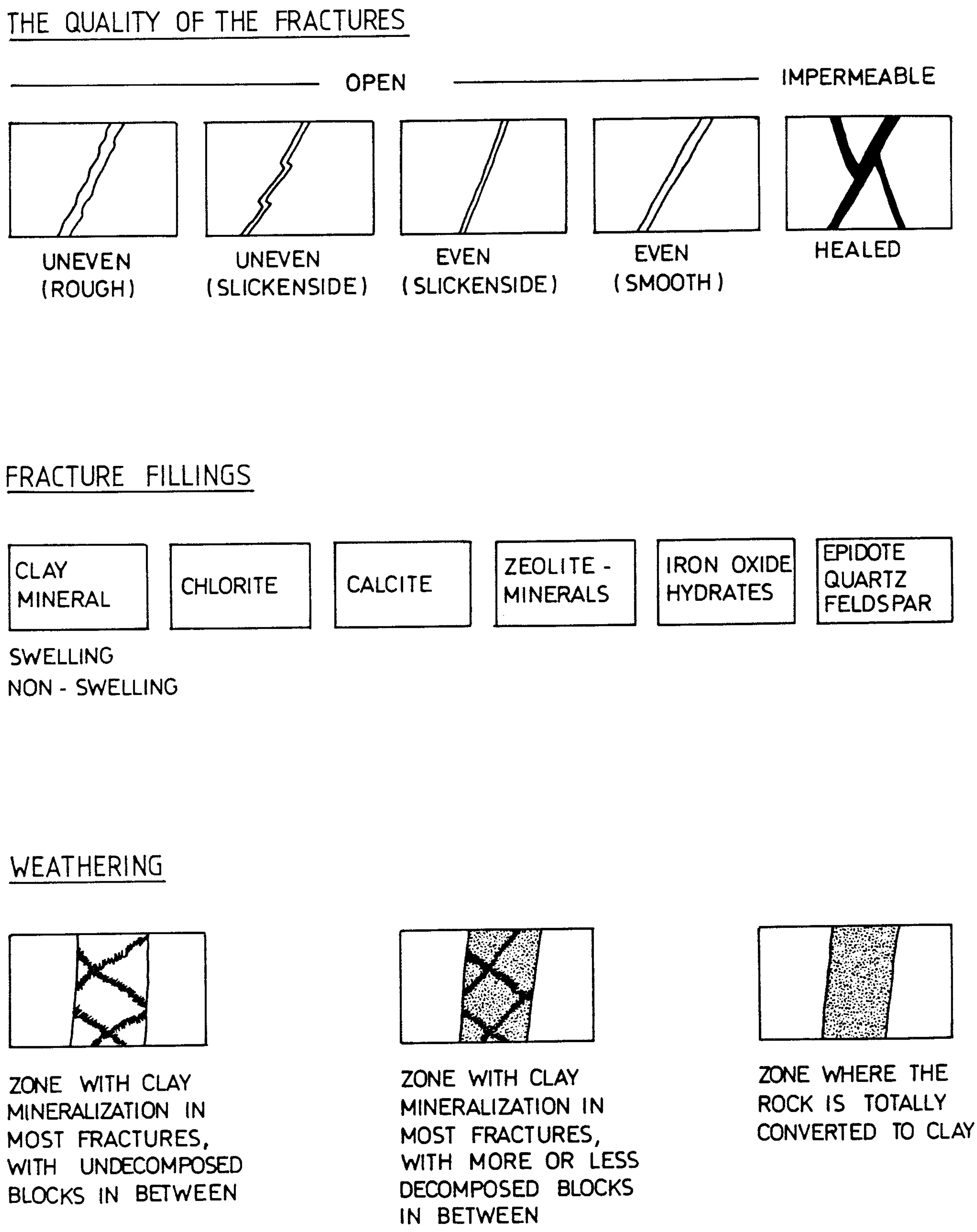


Figure 3.2.3.1   Fracture characteristics

With regard to the mineralogical composition, it has been found in X-ray diffraction analysis that both pulverized bedrock (quartz, feldspar) and actual clay minerals often appear together. Clay minerals can be roughly divided into swelling minerals (smectites) and non-swelling minerals (e.g. kaolin and illite). The total quantity of clay minerals found in a "clay sample" is often < 10%.

"Clay" is very commonly found as a fracture filling. Its capacity for sealing varies, depending upon the plane and type of clay minerals contained. Swelling clay (smectite) - which has the capacity to take up water molecules between the lattice layers - has a good sealing effect in fracture filling.

Epidote, quartz and feldspar are examples of crystallized, well-consolidated fracture fillings in impermeable, healed fractures. Calcite may also be well-consolidated, but relatively rapid release of material in conjunction with water leakage is often found in calcite-filled fractures. There is also often an uneven distribution of the calcite along the fracture plane (with a tendency for druse to develop in major fractures), which reduces its sealing effect.

3.2.5 Weathering

Weathering of a rock mass may be both general and pervasive down to a certain level under the bedrock surface, and extremely localized, in which case it is often associated with a deformation zone. In the present project, it is this latter type of weathering which is of interest. Weathering occurs in its simplest form as clay mineralization along a single fracture. More extensive weathering in zones is divided into five types, defined as follows (cf also figure 3.2.3.1):

- "clay filled fractures", isolated fractures ≤10 cm wide
- "clay vein", isolated fractures >10 cm wide
- "zone with clay mineralization in most fractures, with undecomposed blocks in between"
- "zone with clay mineralization in most fractures, with more or less decomposed blocks in between"
- "zone where the rock is totally converted to clay"

3.2.6 The Rock Stress Conditions

One important factor with regard to the aquiferous properties of fractures and fracture zones is the rock stress conditions. At the time of follow up in the present project, there was, for most of the objects, no information available as to the prevailing rock stresses.

3.2.7 Water Leakage - Fracture Volume

In geological mappings made by BERGAB in tunnels, visible water leakage is divided into three categories, by size: minor leakage (v), moderate leakage(vv) and major leakage (vvv). These are defined as:

- v damp - minor drip
- vv major drip - slowly running water
- vvv fast running water - flushing water

In documentation of the TBM tunnels, (the Kymmen and Saltsjö tunnels) two additional classes of leakage were added:

- vvvv fast flushing water
- vvvvv very fast flushing water

Figure 3.2.7.1 provides a principle sketch of how water follows the flow paths along the fracture surfaces in different fracture situations. Increased fracturing in the rock mass means an increased number of flow paths until the crushing is so pronounced that these flow paths disappear. Fractures from different fracture groups generally differ with regard to aquiferous properties. As mentioned above, the different types of fracture fillings occurring are also of significance. Visible leakage is often well defined and delimited to a small part of a fracture or to the point of intersection between crossing fractures. Thus the water often follows flow paths between which the fractures are virtually impermeable.

It should be noted that, in several cases, the leakage reported from different flow paths in chap. 5 is leakage which occurred after sealing measures had been taken. For this reason, attempts to quantify the presence of water in these zones would also require the collection of information from protocols on water loss measurements and grouting measures taken.

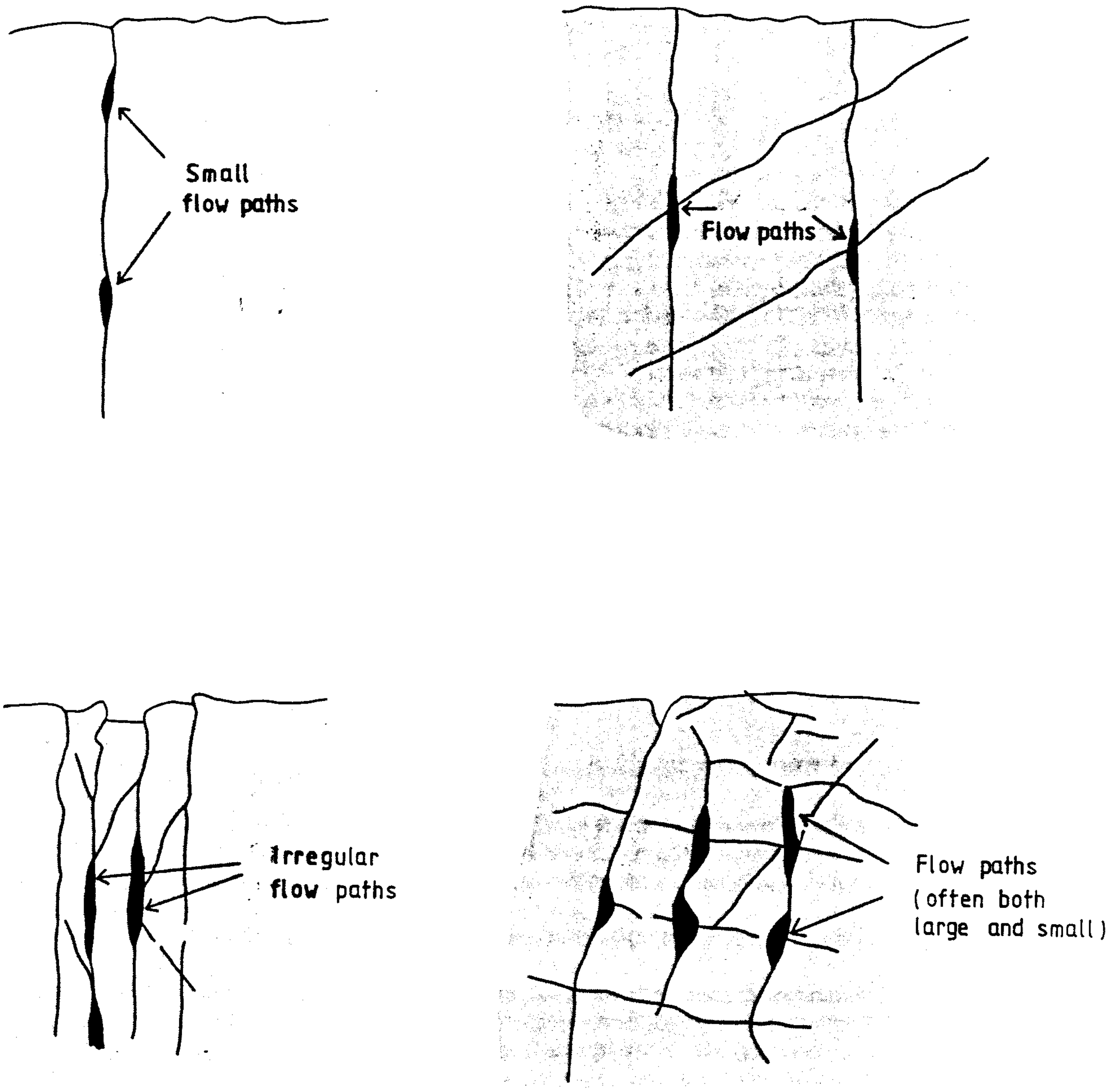


Figure 3.2.7.1 Sketch, in principle, of the presence of water in fractures and crush zones

4 THE PRESENCE OF WATER IN CRYSTALLINE BEDROCK

4.1 BACKGROUND

The presence of water in crystalline bedrock is associated with the presence of fractures in the rock mass. The rock types are impermeable, from a practical point of view. Information about the presence of water in various types of fractures may be obtained through studies of drill holes and of rock caverns, tunnels, shafts, etc. In order to make a detailed study of the presence of water in a rock mass, a detailed survey of the rock conditions and the presence of water in a number of tunnels and rock caverns has been carried out. The indications used to study the behavior of water were both visible leakage with dripping, running, flushing or spraying water, etc. and the distribution of damp and dry fracture surfaces, bedrock sections, etc.

In addition to the detailed field studies made for this project the description is also based on the experience of approximately 25 years of mapping and follow-up of rock and groundwater conditions in underground rock constructions.

4.2 WATER LEAKAGE - REPRESENTATIVITY

In this study, different tunnels and rock caverns had different prerequisites with regard to obtaining clear indications of the presence of water by mapping the presence of leakage.

The best prerequisites for studying the natural presence of water in different types of fractures were in the TBM tunnels. In these tunnels there is no damage zone with fractures caused by blasting which is normally to be found, with varying depths, around rock caverns and tunnels.

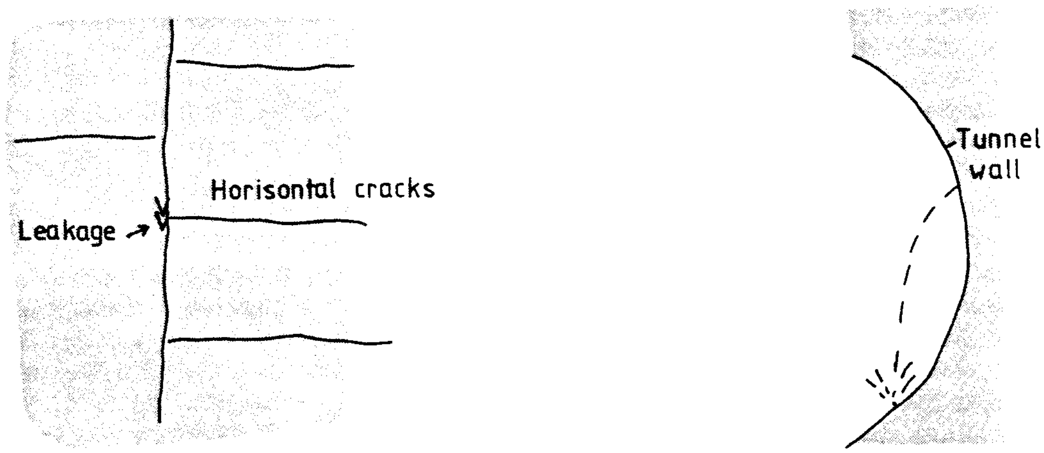
When the damage zone is small (thanks to cautious blasting), natural fractures are very little affected, and there is little new fracturing. In such cases, too, studying leakage gives a basically accurate reflection of the presence of water. One exception to this situation is bottoms where stronger charges of explosives were normally used. This may mean that the rock is slightly "disintegrated", which causes changes to occur in the way the rock reflects the aquiferous qualities. In such bottoms it is normally not possible to map and measure leakage in detail.

A detailed survey of the presence of water in both TBM tunnels and blasted tunnels and rock caverns has shown that the picture of leakage obtained from studying blasted surfaces is in good agreement with the idea of leakage obtained from TBM tunnels. The major difference is that in TBM tunnels, bottoms can be studied as well. Detailed mapping of the presence of leakage thus provide a very good illustration of principles for distribution and appearance of flow paths.

If mapping of water leakage in different types of fractures is to be used to describe the presence of water in rock, a prerequisite is that the picture of leakage given is complete. This has been judged to be the case providing there has been no ground water lowering.

In order to determine how well the extent of a leak along a fracture reflects the width of the flow paths in the area in question, several trials were run in the Saltsjö tunnel. The aim of these trials was to examine what happens if a leak is sealed at its point of outflow. The question of interest was whether the water would appear in the fracture alongside the seal.

Two different points for the study were selected. In one case (section 1/780) a distinct leak was selected from the point of intersection between a long, distinct, steep vertical fracture and a short, horizontal crack. Close to the point of intersection with the leakage, a number of horizontal cracks intersect the vertical fracture (fig 4.2.1).



a) Vertical section of the tunnel wall in 1/780, the Saltsjö tunnel

b) Vertical section in 1/780 m across the tunnel, the Saltsjö tunnel

Figure 4.2.1 A distinct leak in fracture intersection

The steep fracture is formed "en echelon", and has a smooth surface. Some calcite filling is present. The aperture of the fracture is 0 - 1 mm. The horizontal crack is tight and partly filled with calcite. The rock quality is very good in this section.

The leak is classified as $\overset{V}{V}$. The flow rate is 0.105 l/min.

The leaking water was directed into a tube which was applied to the rock wall. A special rapidly-hardening cement (Heidi) was used to attach the tube and to prevent water leakage outside the tube. A simple valve was installed in the tube.

The other experiment was carried out in section 2/122 of the Saltsjö tunnel. Here, a drain ends in a fracture in the roof. The fracture is winding and smooth. Clay and calcite fillings are present. The aperture of the fracture is 0 - 2 mm.

Fracture frequency is higher in this section than in section 1/780, and the bedrock is also more aquiferous.

The leak from the drain is classified as $\overset{V}{V}$. The flow rate is 1.8 l/min. It is impossible to determine whether the leak originated from more than one fracture. The fracture in which the drain ends was sealed with wooden wedges.

Once the valve had been installed in the tube in section 1/780, it was closed. Within one second water began to leak out between the rock wall and the cement. New cement was applied, and the experiment repeated several times. The same result was obtained at every new trial. When the valve was kept closed for a few more seconds, the water penetrated the newly applied cement. No new leaks were observed.

The observations from the second location, in section 2/122, were similar. When the drain was closed, water appeared around the area where the drain was attached. No new leaks were observed, nor was an increase in the flow rate from adjacent leaks noted.

Provided that a cautious blasting has been performed it is assessed that the redistribution of stress occurring around a conventionally blasted tunnel or a TBM tunnel does not to any apprieciable extent affect the picture of leakage as it can be studied in the completed tunnel, with regard to location, scope or size. In most cases, if the ground water pressure is maintained, the picture of leakage remains constant from the time of drilling/blasting and onwards, with regard to location and size. The picture of leakage is only changed when fracture fillings are washed away.

The trials described above indicate that the picture of leakage that can be studied in a TBM tunnel where the ground water pressure is maintained, gives a full picture of the distribution and appearance of the flow paths water in the bedrock. This is also generally the case with regard to conventionally blasted tunnels where cautious blasting has been used.

4.3 THE AQUIFEROUS PROPERTIES IN DRILL HOLES EXAMINED

It is confirmed in the examination of drill holes that water normally flows in bedrock either in flow paths in separate fracture planes or in more complex flow paths in fracture and crush zones. Only in exceptional cases does water flow along most of a fracture plane.

Thus, when probing or exploratory drilling takes place, one hole that intersects with a fracture may produce water, while a nearby hole through the same fracture may be dry. The picture is further elucidated in tunnels where pregrouting has been carried out. In tunnels requiring extremely good impermeability, drill holes are sometimes made for the grouting screen, at a distance of $\leq$ 1 m between the ends of the drill holes. This may mean drilling twenty or more holes in the section of the bedrock which is to be sealed. When trials are made with respect to injecting water into the holes, some of them often appear to be interrelated. A varying number of holes are dry. Mapping of the section of the tunnel subsequent to grouting and blasting often presents leaking fracture planes despite the fact that these planes have been penetrated and grouted with cement. In most cases, satisfactory sealing results has been obtained through post-grouting with cement, which indicates that the fractures were not too narrow to be sealed with cement, and that the problem was attributable to the fact that the drill holes and the injection suspension did not make contact with all the flow paths in the rock mass.

4.4 LEAKAGE IN DIFFERENT TYPES OF ROCK

The picture of leakage which is commonly associated with different rock types has to do with their brittleness and their related tendency to develop fractures when the bedrock is under strain. Generally speaking, acidic, crystalline deep rock types (granites) are more brittle, more fractured, and more aquiferous than more mafic deep rock types (such as diorite and gabbro), in which the frequency of fracturing is usually less, as is the length of the fractures.

In tunnels and rock caverns, walls and ceilings in mafic deep rock types may often be completely dry, while in granite rock surfaces there is often not only point leakage but also general surface dampness.

The situation is similar with regard to metamorphose rock types (gneisses, amphibolites, etc.). Acidic original rock types generally give rise to more brittle gneisses than more mafic original rock types.

An even more important factor with respect to the water bearing of gneisses is the degree of conversion to veined gneiss and migmatite. Thus, for example, sedimentary veined gneiss may have strong properties with regard to strain, which gives rise to little fracturing and dry rock mass in places.

In tunnels and rock caverns in sedimentary veined gneiss, large surfaces may show an absence of visible leakage and be absolutely dry.

Amphibolites are often found as small deposits in other rock types. Large occurrences of amphibolites normally have few fractures and are impermeable. However, there is often leakage at the contact surface between amphibolite and adjacent rock types.

Similarly, diabase veins may only show negligible leakage, while the contact surfaces with adjacent rock types may be highly aquiferous.

Veins of fine-grained granite or aplite may be locally highly fractured and aquiferous. This is also true for local veins of pegmatite.

In rock caverns and tunnels one and the same vein of, for example, fine-grained granite, may present absolutely no leakage or indistinct dampness a long stretch and then in an adjacent area be partly crushed and fractured, with small leaks in most of the fractures.

4.5 LEAKAGE IN DIFFERENT TYPES OF FRACTURES

As has been stated above, ruptural deformation of a rock mass gives rise to fracture patterns and characteristics determined by the rock types present. In addition to the rock types, the fracture pattern and characteristics are dependent upon the degree of anisotropy of the rock mass, the intensity of the deformation, whether or not there have been repeated deformations, the rock stress situations, etc.

The picture of the presence of water in different types of fractures reflected in the findings of detailed mapping of visible leakage in tunnels and rock caverns indicates that the water is often present in flow paths along a fracture plane. Thus leakage may be concentrated to one very small section of a fracture, while the surrounding parts of that same fracture show no trace of water leakage. One special case occurs when there is only leakage in the point of intersection between two "dry" fracture planes (figure 4.5.1).

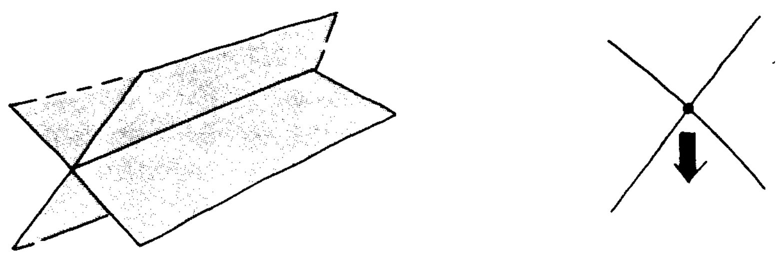


Figure 4.5.1 Flow path and leakage at the point of intersection between two "dry" fracture planes.

The horisontal sheeting (stress relief plane) in granite provides an excellent illustration of the aquiferous properties of flow paths in isolated fractures. These fractures occur at decreasing frequencies in relation to depth. In surface parts of the bedrock, leakage/flow path occurs along long stretches of these fractures (figure 4.5.2).

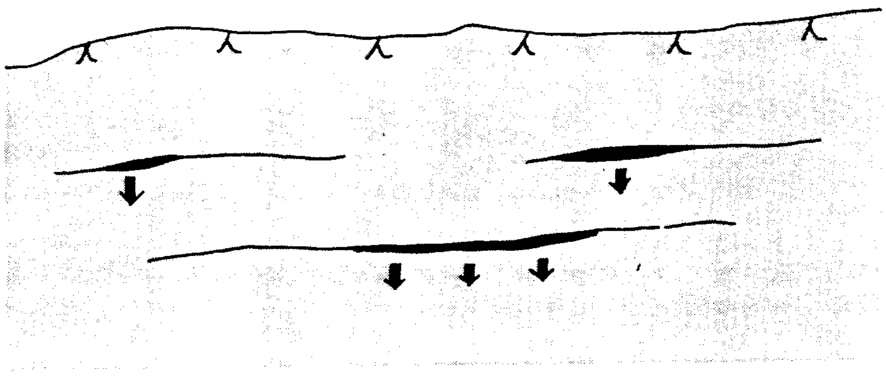


Figure 4.5.2 Flow paths in granite with superficial horisontal sheeting.

Deeper down in the bedrock, as mentioned above, horisontal sheeting appears with less frequency, and often in groups of fractures (figure 4.5.3). The flow paths may be concentrated only to one fracture in a group, and only to a small part of that fracture.

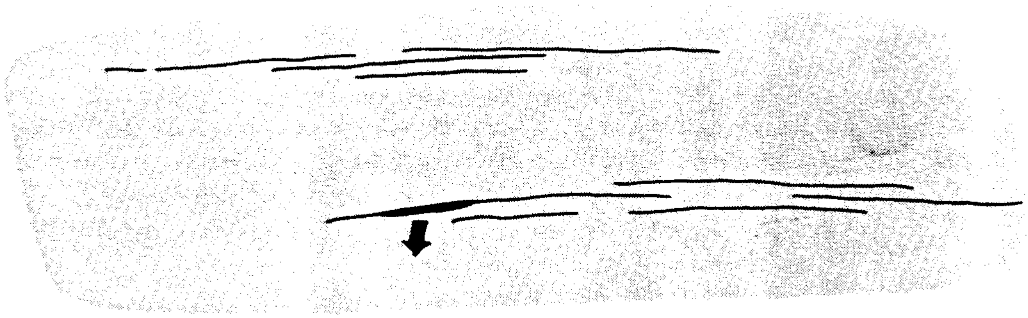


Figure 4.5.3 Small drapery flow paths in deep horisontal sheeting/stress relief fractures in granite.

Similar pictures of leakage may be found in fractures along the plane of schistosity in anisotropic rock, for example in gneiss (figure 4.5.4)

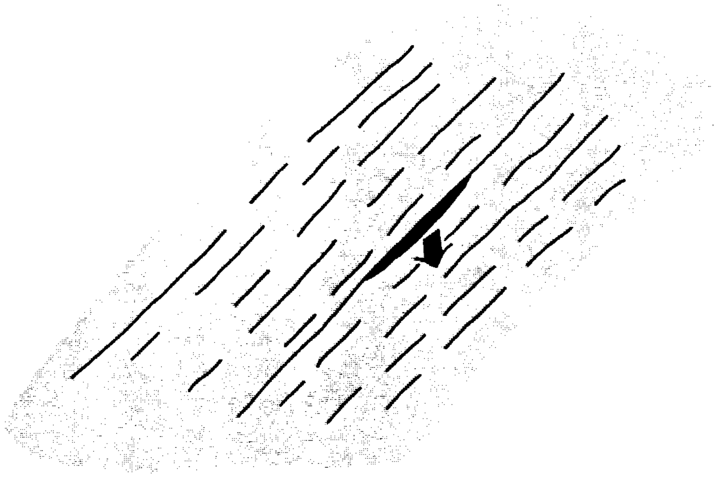


Figure 4.5.4 Leakage in a fracture plane developed along the plane of schistosity in gneiss, for example.

The flow path is normally limited to a very narrow section of the fracture. It is best described as narrow drapery leakage. This type of leakage is less common in steep schistosity than in a subhorizontal schistosity.

One special case of flow path in anisotropic bedrock is a flow path along a fracture plane between amphibolite and gneiss. The amphibolite may then appear as a slab in the gneiss, with one dry contact side and the other contact side leaking.

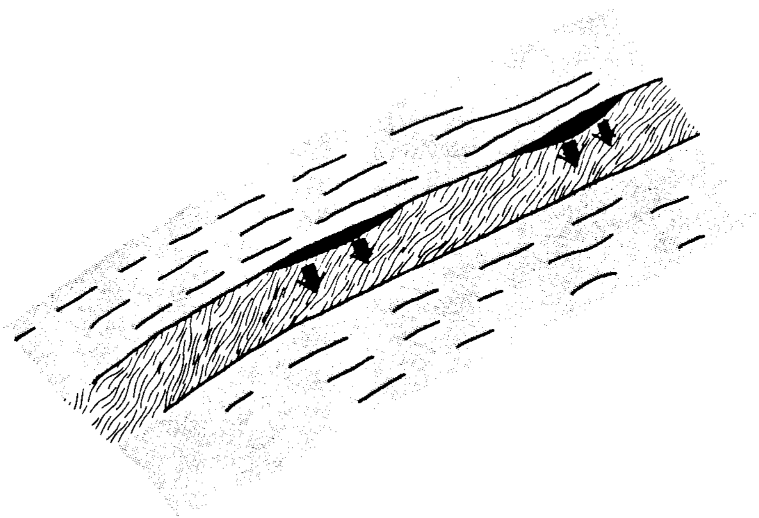


Figure 4.5.5 Drapery leakage along a fracture in the contact between amphibolite and gneiss.

Leakage appears in places as wide drapery leakage, with a length of half a meter. In these cases, too, there is more leakage and leakage is more common in gently dipping planes of schistosity than in steep ones. There may be a similar picture of leakage in one of the contact sides between an aplite vein and the surround-ing granite. In such cases, however, there may also be small point leaks in conjunction with local fracturing in the aplite, which is brittle to strain (figure 4.5.6).

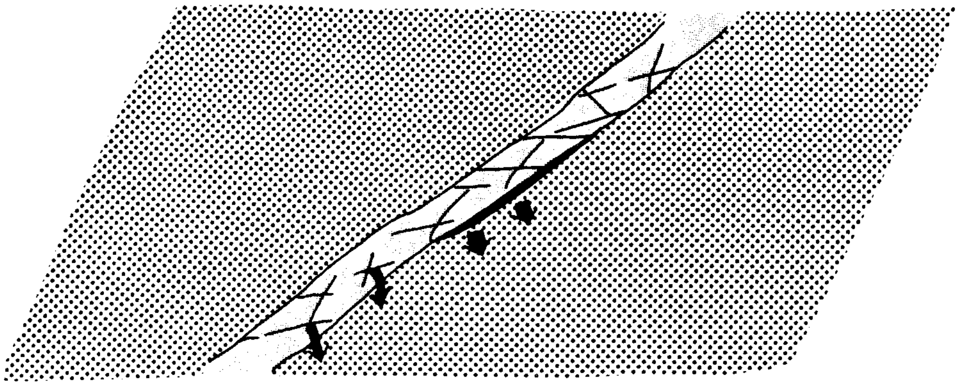


Figure 4.5.6 Drapery leakage along a fracture in the contact between aplite and granite. Locally, small point leaks may also appear in the partly fractured aplite.

In the examples described above, the blocks of rock surrounding the fractures have a large contact surface in relation to one another. This is the case in contact fractures, owing to differences in tensile properties and in stress relief fractures deeper in the bedrock.

A similar pattern of leakage/aquiferous properties in isolated fractures may be found where there are one or more fracture groups in the rock mass. This applies particularly to the development of plane fractures with negligible movement along the fracture plane. The contact surface is very large and there will only be leakage in a small number of fractures in one fracture group. These are normally point leakage or with maximun width of approximately 1 - 2 decimeters (figure 4.5.7).

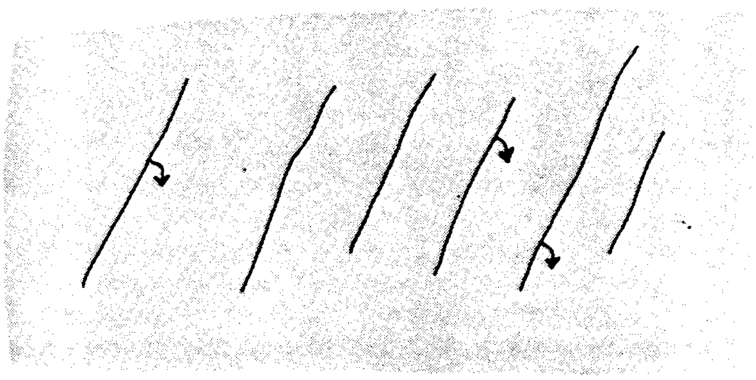


Figure 4.5.7 Fracture group showing isolated point leakage.

When there are two intersecting fracture groups, the proportion of visible leakage tends to increase. In such cases one of the fracture groups usually has more, and more extensive, leakage than the other. Moreover, small point leakage may occur along a number of points of intersection (figure 4.5.8).

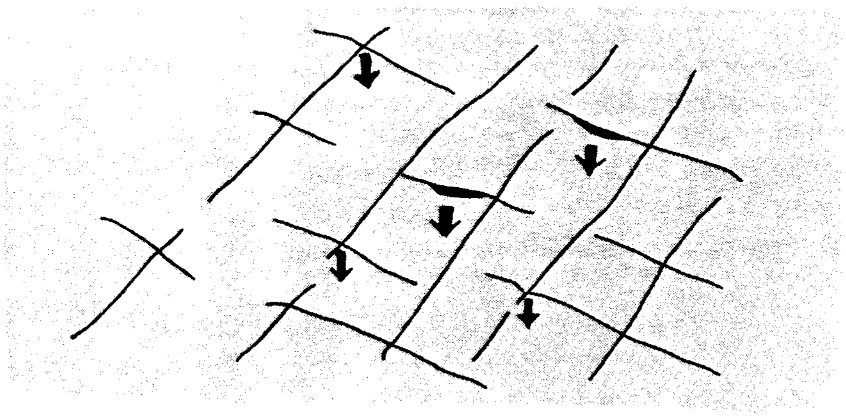


Figure 4.5.8 Point leakage - small flow path leakage in two intersecting fracture groups

When there are three intersecting fracture groups, the proportion and size of leakage tends to increase as compared with the case of two intersecting fracture groups. In such cases there tends to be drapery leakage, primarily in gently dipping fractures (Figure 4.5.9).

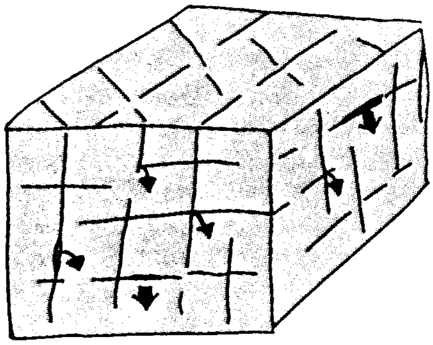


Figure 4.5.9 Drapery and point leakage in three intersecting fracture groups

4.6 LEAKAGE IN RELATION TO TYPE AND LENGTH OF FRACTURE

In the cases of intersecting fracture groups thus far described, there has normally been very small movements occurring in conjunction with the genesis of the fractures. The fractures appear in systematically uniform patterns.

When there is greater tectonic influence on the bedrock, the water bearing along individual fracture planes is clearly dependent upon the genesis of the fractures. Thus there is a clear difference between tension and shear fractures. Tension fractures may appear "en echelon" and be relatively short, but they may also appear as long-lasting, open fractures (Figure 4.6.1).

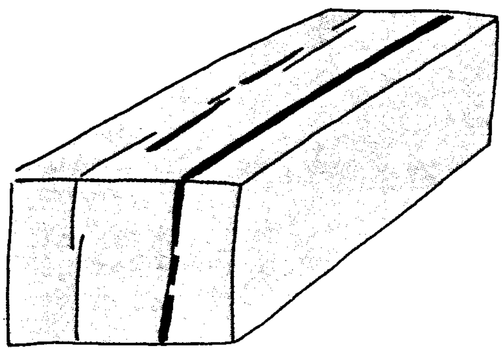


Figure 4.6.1 Tension fractures "en echelon" and as long-lasting, open fracture in the direction of the primary deformation.

In short fractures "en echelon", the fractures are normally not aquiferous, or very little so. Where the fractures are longer and distinctly developed, they may be clearly open and show marked aquiferous qualities along a large part of the fracture. However, in many cases there is a fracture filling such as calcite or quartz instead of water. In fractures with a calcite filling, flow path leakage may appear where the calcite has been partially dissolved.

The shear fractures are normally negligibly aquiferous. When the fractures developed, the blocks of rock moved, under great pressure and high friction, along the fracture planes. Contact metamorphose minerals were developed, and the fractures were virtually impermeable. When there is later bedrock movement, however, the characteristics of the shear fractures may change, resulting in an increase in aquiferous qualities (figure 4.6.2)

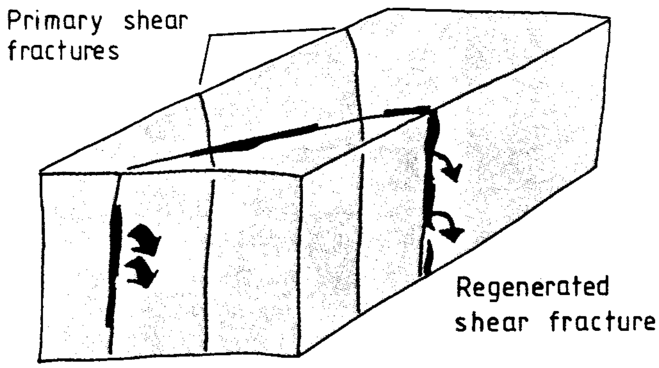


Figure 4.6.2 Negligible aquiferous qualities in a primary shear fracture. A regenerated shear fracture may present distinct flow paths resulting in both drapery and point leakage.

4.7 FRACTURE FILLING - AQUIFEROUS PROPERTIES

The occurrence of fracture filling has a major influence on the aquiferous properties of a fracture. The most common fracture fillings are calcite and clay. Other common fracture minerals are chlorite, quartz and limonite. In calcite and clay fracture fillings there is often more or less point-shaped leakage (figure 4.7.1)

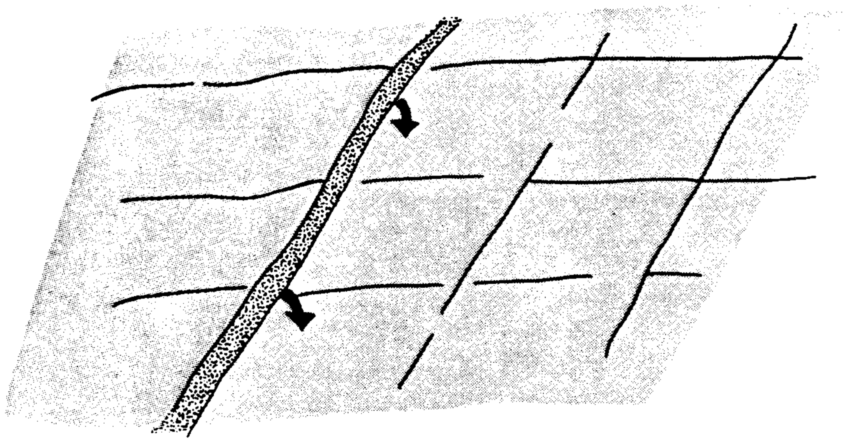


Figure 4.7.1 Point-shaped leakage in calcite or clay-filled fracture.

When the leaks are not sealed, they generally spread relatively quickly in both scope and size.

Fractures filled with quartz generally present no leakage.

4.8 THE QUALITIES OF THE FRACTURE SURFACE - TYPE OF LEAKAGE

This text has already indirectly elucidated the significance of the fracture surfaces with regard to the presence of water. Smooth fracture surfaces with large contact surfaces between the blocks of rock provide very little potential for the creation of long-lasting flow paths along the fractures. However, limonite coating on this type of surface, too, indicates that there may have been a very weak flow - virtually stagnant water - without any actually visible leakage having been noted.

In fractures where the contact between adjacent blocks of rock is less good, a fracture may show one or more point or drapery leaks. Gently dipping fractures often present some drapery leakage. This is natural, as this type of fracture usually has developed as stress relief. Depending upon their length and their proximity to the bedrock surface, such fractures display sections of varying size where they are completely open. The fracture surface may be slightly arched, with a somewhat rough surface structure.

4.9 LEAKAGE IN AND NEAR TECTONIC ZONES

The behavior of water in and in close contact to tectonic zones, as may be seen by studying the size, distribution, etc. of leakage, normally presents a highly complex pattern, with wide variations among different types of zones.

In tension zones with developed slaty cleavage, often running parallel to groups of fractures in the surrounding rock, the fractures may be highly aquiferous, and sealing measures absolutely essential for tunneling (figure 4.9.1)

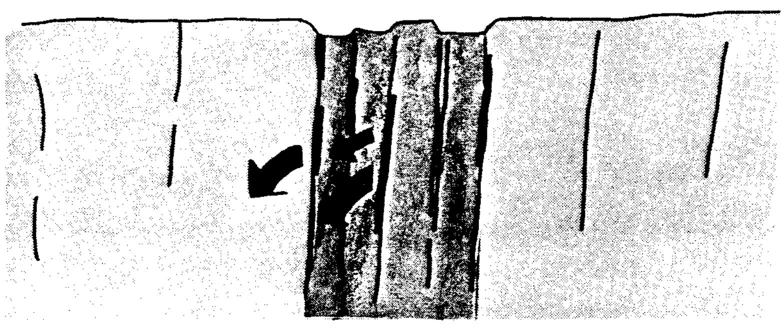


Figure 4.9.1 Considerable water leakage along large parts of the fractures in a tension zone.

In a corresponding shear zone of slaty cleavage, parallel to a fracture group in the surrounding rock, the fractures are often basically impermeable. Only dampness or small point leaks appear (figure 4.9.2)

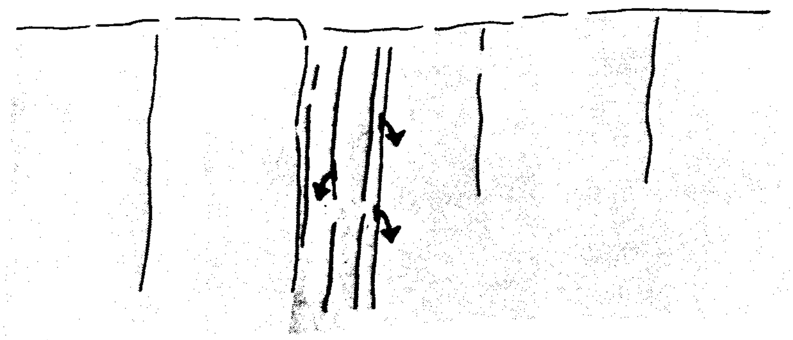


Figure 4.9.2 Slight aquiferous qualities with only small point leakage in shear zone of slaty cleavage.

When the shear zone presents a pressed, thin-slaty cleavage, there is usually no visible leakage. A thin film of chlorite or clay often covers the smooth fracture surfaces, and only dampness in the exposed rock in the zone may be noted (figure 4.9.3).

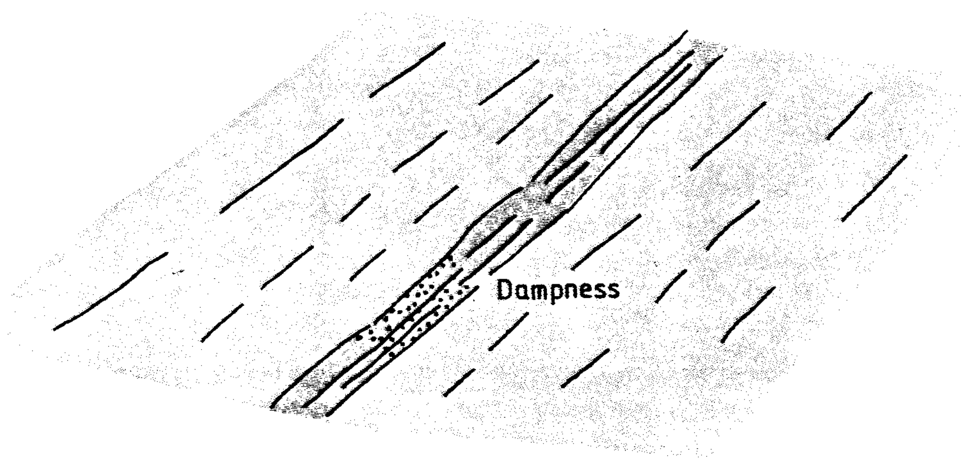


Figure 4.9.3 No visible leakage in slaty shear zone parallel with the schistosity.

In tectonic zones with increased fracturing, different types may be found. The aquiferous qualities will depend on the genesis of the zones, the degree of fracturing, and the presence of fracture filling. In tension zones where the fracture pattern gives rise to a blocky or partly crushed rock, there may be considerable water leakage in places. This is particularly true where there is little fracture filling (figure 4.9.4).

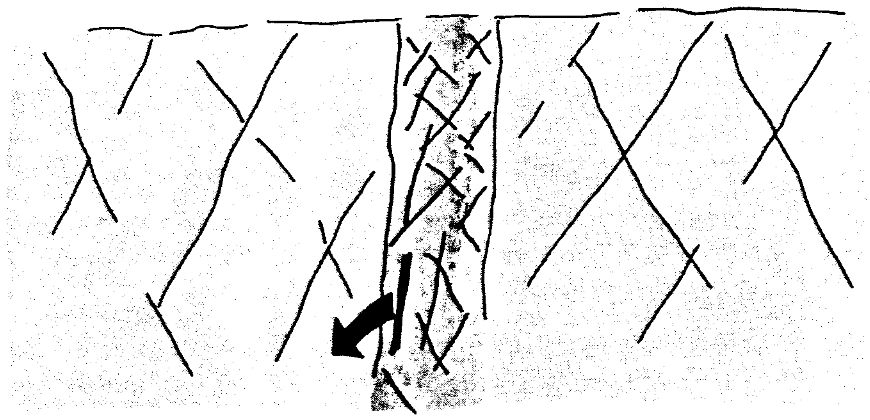


Figure 4.9.4 Tension zone with blocky-partly crushed rock. Considerable local leakage.

In these types of zones where there is a great deal of fracture filling, there will only be small to moderate point leaks (figure 4.9.5).

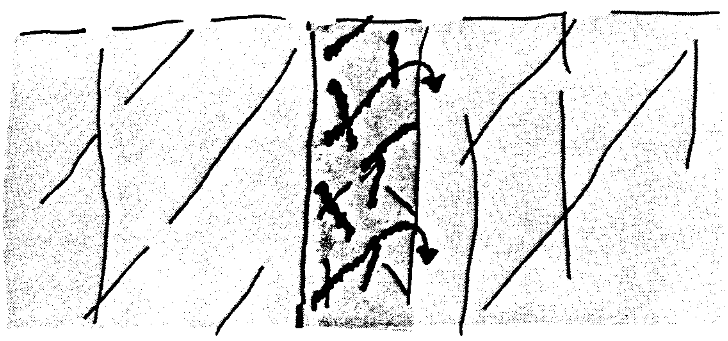


Figure 4.9.5 Tension zone with blocky-partly crushed rock. Only point leakage owing to extensive fracture filling.

In shear zones with blocky-partly crushed rock, the degree of crushing is normally decisive with regard to aquiferous properties. Thus, the aquiferous qualities increase in relation to increased fracturing, up to a given point (figure 4.9.6).

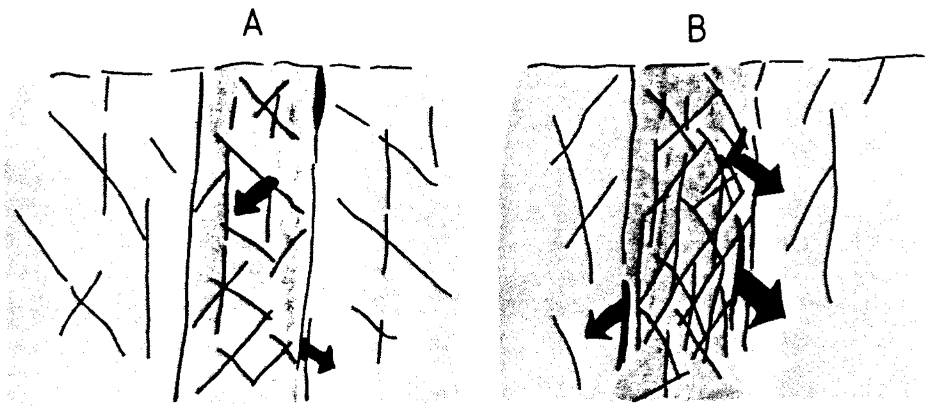


Figure 4.9.6 Shear zones often present increased aquiferous qualities in relation to increased fracturing. Point and drapery leakages are greater in zone B than in zone A.

Increased fracturing also leads to a tendency for the largest leaks to be in areas of contact between the zones and the surrounding rock. This is attributable to the fact that the central sections of the zones are far too highly crushed to allow for any aquiferous flow paths (figure 4.9.7).

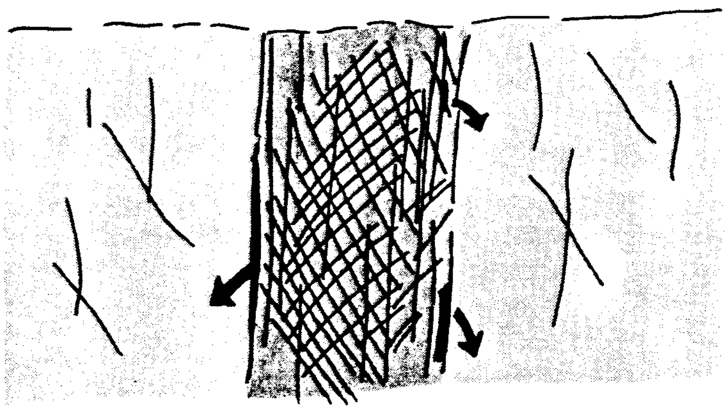


Figure 4.9.7 Increased fracturing in shear zones usually leads to water leakage in or close to the contact to the surrounding rock.

Further increased fracturing and crushing of the rock in such zones further decreases its aquiferous potential, and fractures filled with calcite, clay, and other minerals dominate. In such cases they are hardly aquiferous, and there can only be insignificant point leakage (figure 4.9.8)

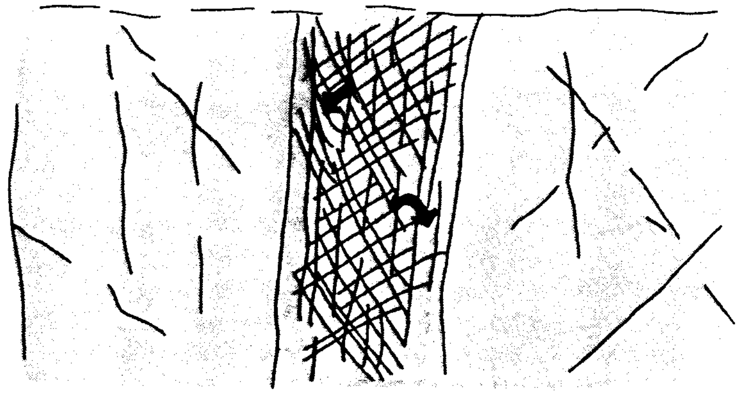


Figure 4.9.8 Intensively fractured and crushed rock in a shear zone. The zone is either totally impermeable or there are only small point leaks.

Shear zones which have developed what is called overthrust zones generally show the same correlation between degree of crushing and aquiferous properties as steep shear zones. The phenomenon of concentration of the aquiferous properties to the places where the zone is in contact with the surrounding rock is, however, accentuated considerably in overthrust zones. In such cases the clearly dominant picture is one in which the aquiferous properties are concentrated to the upper contact surface. Overthrust zones with extensive fracturing, crushing and clay alteration, may be highly aquiferous at the contact surface between the zone and the hanging wall (figure 4.9.9).

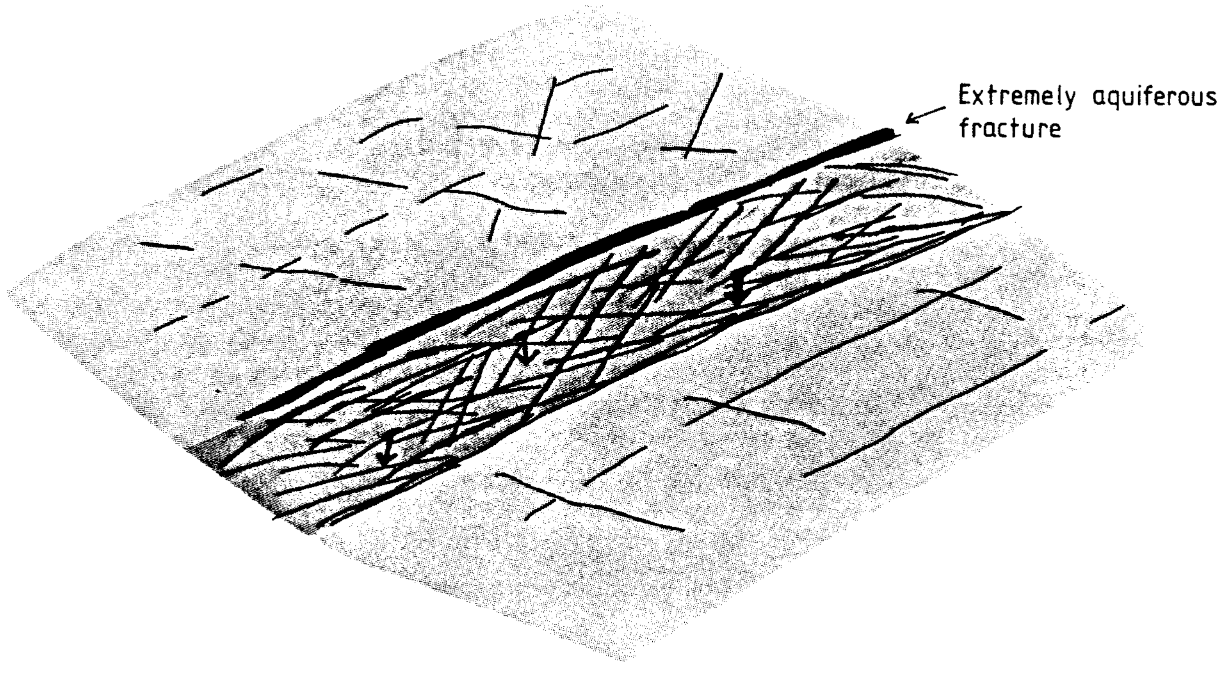


Figure 4.9.9 Zone with extensive fracturing, crushing and clay alteration. There are extremely aquiferous fractures along the contact surface with the hanging wall.

The examples of the aquiferous properties of various tectonic zones presented above give an oversimplified explanation, primarily in order to indicate the main differences. In reality these zones are often highly complex. For example, a zone may comprise narrow sections of crushed and weathered rock surrounding a core of partly crushed rock. The section of the zone thus described may, in turn, be surrounded by blocky rock creating the contact with the surrounding bedrock. Most of the leakage will often be found in the blocky areas of the zone (figure 4.9.10). The various fracture minerals serving to more or less seal the fractures are another, separate, compounding factor.

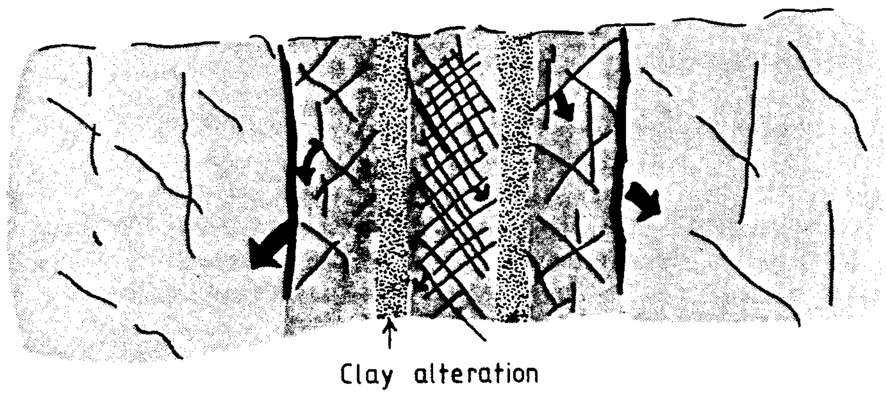


Figure 4.9.10 Complex zone, with blocky and partially crushed areas divided by crushing and clay alteration in impermeable sections.

Just as the zones often present a complex appearance which determines where they can be at all aquiferous, zones have also been regenerated when new stresses in the bedrock have occurred. At such times, even highly crushed zones, previously relatively or completely impermeable owing to the presence of various fracture minerals, may become highly aquiferous. Often the new stresses have only resulted in the breakup of part of the healed zone (figure 4.9.11).

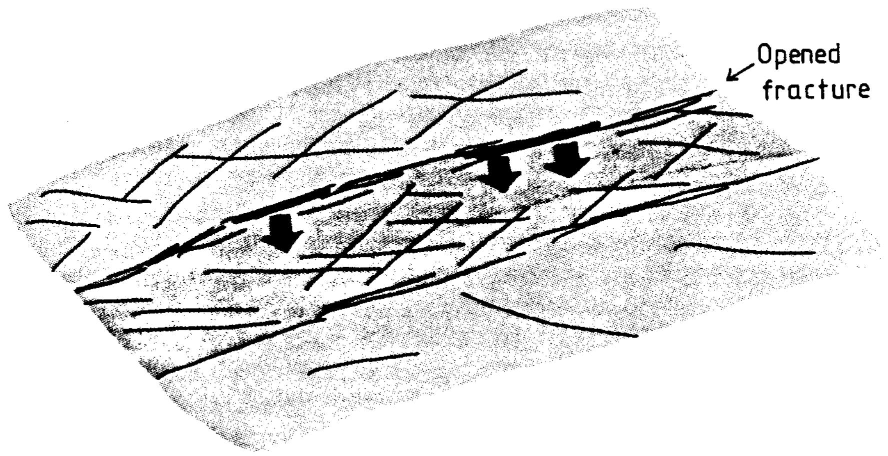


Figure 4.9.11 Regeneration of the healed fractures in a crush zone, with development of open aquiferous fractures in only a small part of the old zone.

5 ANALYSIS OF HYDROGEOLOGICAL CONDITIONS

5.1 BACKGROUND

The following analysis are primarily based on the documentation carried out on the Kymmen and Saltsjö TBM tunnels, which focused on presenting a highly detailed mapping of the existing leakage. Secondarily, in an attempt to elucidate regional similarities and differences in southern and mid-Sweden, these issues have also been analyzed on the basis of the mappings carried out in the drilled and blasted tunnels and rock caverns including the Bolmen tunnel, Forsmark III, SFR, water supply and sewage tunnels in Göteborg, the Stockholm subway and test tunnels in Stripa.

There was extensive grouting in all the tunnels except the Kymmen tunnel and the tunnel at Stripa. This led to the reduction of leakage and to the virtual prevention of ground water lowering. There is no information for the Kymmen tunnel with regard to the extent to which leakage has led to ground water lowering. It is probable that there has been some lowering in conjunction with the largest tectonic zones, and this may have led to slightly reduced leakage in some sections. However, the documented distribution and leak inflow are assessed as giving a reliable picture of the relative differences between different rock types, zones and fractures.

The depths under ground level of the tunnels studied vary between 10 and 360 m. The prevailing ground water pressure at tunnel level is assumed, for the sake of simplicity, to correspond to a ground water level at the surface level.

Pregrouting was carried out in several of the drilled and blasted tunnels as well as in the Saltsjö tunnel. Particular attention was paid to tectonic zones which were indicated to be highly aquiferous at probing. Pregrouting generally prevents extensive leakage, and grouting may also change the distribution of leakage. For these reasons, analysis of the correlation between visible leakage and different types of rock, zones, fractures, etc also must include information as to whether and to what extent grouting was carried out. Since the quantity of grout used gives a rough idea of the fracture volume filled, comparisons between different necessary grouting efforts may be used to analyse the fracture volume in different qualities of rock. A description of the grouting process must, then, include information as to the number and distribution of drill holes, the quantity and type of grout used and the grouting time. It is a prerequisite for such an analysis that the grouting process used in the different tunnels be equivalent, and that the work have been carried out so that the grout was mainly used to fill fractures in a limited zone around the tunnel.

5.2 QUANTIFICATION OF LEAKAGE

Wherever possible, the detailed documentation of leakage in the Kymmen and Saltsjö tunnels has included measurement of leak inflow. The findings of these leak measurements in the Kymmen tunnel were as follows:

v = < 0.01 l/min

vv = 0.01 - 0.2 l/min

vvv = 0.2 - 1.5 l/min

vvvv = 1.5 - 6.5 l/min

vvvvv = > 6.5 l/min

Corresponding findings for the Saltsjö tunnel were as follows:

v = <0.04 l/min

vv = 0.04 - 0.3 l/min

vvv = 0.3 - at least 1.08 l/min

These figures are only to be taken as indications. Owing to practical difficulties involved with leak inflow measurement, the number of measurements is too small to be used to draw up any general limits. This is especially true for large and extensive leaks.

The figures reported by Christiansson & Bolvede (1987) from a follow up in SFR may be mentioned by way of comparison. This mapping was carried out with leak classification for dampness, dripping and running water. Very few measurements were made except where there were quite large flows of water. Estimates indicate that large flows of over 1.5 l/min should be within ± 0.5 dl/min. It is also, unfortunately, stated that accuracy for smaller flows is no better. The report gives an estimate of the leak inflow at each point of leakage. These qualities, as given in l/min, generally apply to several leaks on the area. No attempt has been made, via quantification in l/min to distinguish between the subjective classifications of v , vv and vvv . In the few cases where the tables state that the leakage is only for a single leak, the following approximate figures may be given:

v ≤ 0.1 l/min

vv > 0.2 - ≤ 0.7 l/min

vvv > 0.7 l/min

It may also be seen that the classification of drip (vv) is broader in the SFR figures. It is possible that the limit between vv and vvv should be shifted downward (cf above, where 0.5 l/min denotes heavy flow). At a point around 0.4 l/min the differences between the quantifications made at the different constructions cease to be so great.

Using the same classification for the different constructions would give the folowing figures, considering that actual measurements have been taken in the Kymmen and Saltsjö tunnel while mainly estimations have been done in the SFR:

v = < 0,04 l/min

vv = 0,04 - 0,3 l/min

vvv = 0,3 - 1,5 l/min

vvvv = 1,5 - 6,5 l/min

vvvvv = > 6,5 l/min

5.3 THE AQUIFEROUS QUALITIES OF THE BEDROCK

The aquiferous capacity of the crystalline bedrock is dependent on the volume of the communicating open fractures or flow paths along otherwise impermeable fracture planes. The rock between the fractures is virtually impermeable.

Capacity varies not only between different rock types but also within one and the same type of rock. The differences between different rock types are primarily attributable to their varying degrees of brittleness and their concurrent tendencies to develop fractures under conditions of stress in the bedrock.

Variations in hydraulic capacity between one and the same type of rock are attributable, for example, to variations in the fracture pattern and characteristics, deformations which have in the bedrock, and the prevailing rock stress conditions.

5.4 THE DISTRIBUTION OF WATER IN THE BEDROCK

A compilation and analysis of the inflow and distribution of water leakage along several of the documented tunnels has been made. The compilation indicates, in all the tunnels, that most leakage occurs in zones with increased fracturing of the rock mass. Between these zones, the leakage is associated with individual fractures. In some of the tunnels there are completely dry sections. These normally occur in bedrock with only low fracture frequency.

In the Bolmen tunnel, which is some 80 km long, the greatest inflow was noted at the points of intersection with regional tectonic zones. Semiregional fracture zones present less leakage than regional zones, but considerably more than local fracture zones. Major leaks between the zones are associated with the contact surfaces between gneiss and amphibolite, and with tension fractures (Stanfors 1986 and 1989).

A similar description of the behavior of water has been given of the Forsmark tunnel by Carlsson & Olsson (1977). In this tunnel, highly fractured sections with a great deal of leakage alternate with completely impermeable, dry sections. Approximately 60% of the leakage occurs in the tectonic zones. These zones account for approximately 24% of the entire tunnel length. The leak inflow in the zones is approximately 4 l/min,m as compared with the inflow in the rest of the tunnel, which is only 0.8 l/min,m In the zones with the highest leak inflow it is 8.3 l/min,m., which is about twenty times greater than in the driest zones, and more than twice the leak inflow in the other tectonic zones.

In the study made by Christiansson & Bolvede (1987), the water leakage in the SFR tunnel is primarily described as dripping and damp spots, with some running water where large zones have been passed. Approximately half of the total water leakage in the SFR tunnel, 650 l/ min, originates in the Singö fault zone and in a gently dipping zone in the lower construction tunnel. This means that approximately 10% of the total length, including the tunnels, rock caverns, shafts and silo (approx. 4.5 km) accounts for 50% of the leakage, despite grouting in these zones.

The same pattern is to be found in the follow up and assessment made along the tunnels in the Göteborg and Stockholm areas (Palmqvist 1983, Palmqvist & Lindström 1988). The water leakage and the need to take sealing measures are greatest in tectonic zones with increased fracturing intensity. Between the zones the water leakage and the need to take sealing measures both decrease in relation to decreased fracturing intensity.

A summary of the detailed mapping indicates that along the Kymmen TBM tunnel, the major leaks either correspond, on the whole, to the location of the tectonic zones or appear in conjunction with them. Sections of general dampness in the tunnel also correspond, to a large extent, to zone sections and/or sections of major leakage (figure 5.4.1). Approximately 75% of leakage along the tunnel occurs in the tectonic zones (Palmqvist & Stanfors 1987).

Crush zones comprise 15% of the length of the Kymmen tunnel, and account for 47% of the leakage $\geq \check{V}$. Leakage per meter of crush zone is approximately 17 times as great as leakage per meter in the rock between the crush zones.

The same picture may be seen in the parts of the Saltsjö tunnel studied, where leakage is generally associated with the tectonic zones (Palmqvist & Lindström 1988).

According to the follow up along the entire Saltsjö tunnel made by Lundström & Rydbäck (1989), more than 50% of the length of the tunnel is impermeable. The distribution of the aquiferous qualities in the rock outside the actual zones is also often highly irregular.

The very detailed mapping of leaking water in the Stripa test tunnel indicates that the water does not exhibit uniform behavior in the bedrock, but rather appears to be localized, with large dry sections between the wet ones (Abelin & Birgersson 1987). This uneven distribution may be seen in figure 5.4.2.

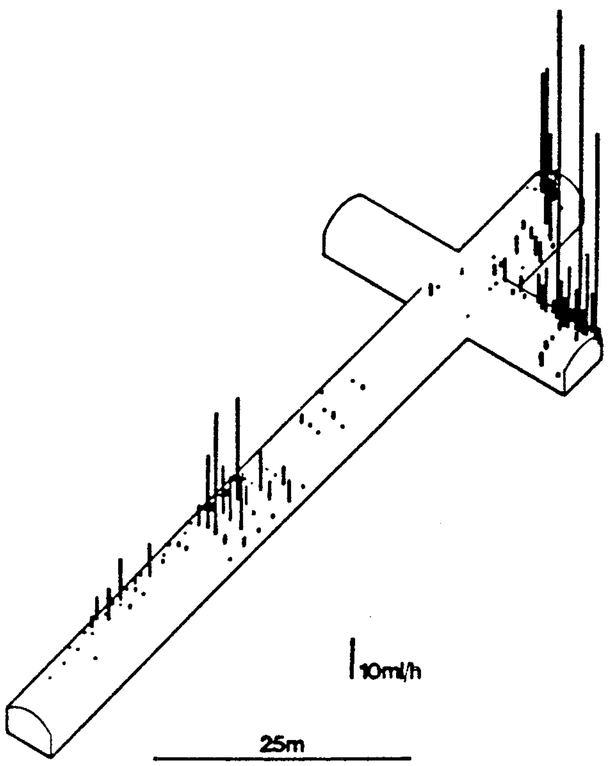


Figure 5.4.2. Water inflow rates into the test site prior to the drilling of the injection holes. (Abelin & Birgersson 1987)

5.5 AQUIFEROUS PROPERTIES OF DIFFERENT ROCK TYPES

It is only possible to make a meaningful comparison of the aquiferous qualities of different types of rock under equivalent tectonic conditions. This means that comparisons should only be made in tectonically homogeneous sections of bedrock. The aquiferous properties of a granite in one tectonic region may, for example, differ from the properties of a granite from another tectonic region. In the descriptions given below, each tunnel, with the exception of the tunnels in the Forsmark and Göteborg areas, has been assumed to represent a separate tectonic region.

In the Forsmark tunnel Carlsson & Olsson (1977) have studied the water inflow in the two primary types of rock, gneiss-granite and paragneiss (sedimentary origin) outside the tectonic zones. The leak intensity in the gneiss granite is 2.3 l/min, m. The corresponding value in the paragneiss is 1.3 l/min,m.

Usually, the aquiferous fractures in the paragneiss are part of the schistose structure of the rock mass, while the fractures and thus also the water inflows in the gneiss granite appear to occur more independently of the rock structure. In the gneiss granite, the fracturing shows a regular pattern. The horizontal fractur groups are cut of by vertical fracture groups. This rectangular network of fractures forms at least one co-operative water bearing system. In the paragneiss, no such co-operative system is developed and the fracture groups are dominated by the schistose rock structure. In the gneiss granite, the horizontal fracture group is especially well developed near the rock surface but seems to vanish at greater depth (Carlsson & Olsson 1977).

In Göteborg, comparisons may be made between a slight schistose granodiorite (the Ale tunnel) and an orthogneiss (magmatic origin) with layers of amphibolite (the Partille tunnel).

With respect to the grouting (quantity of cement per meter of tunnel), the visible leakage (per meter of tunnel), and total inflow, the slightly schistose granodiorite is less aquiferous than the gneiss in the Partille tunnel. The dominant type of aquiferous fracture in the Partille tunnel is fractures along the plane of schistosity. In the Ale tunnel the dominant types of aquiferous fractures are fractures along the plane of schistosity and steep fractures at an obtuse angle to the plane of schistosity.

The degree of schistosity is significant to the development both of fracture zones and of long, distinct fracture planes along the schistosity. This is particularly true for the tunnels presented here, with one or two dominant fracture groups. There is, thus, no real blocky rock providing the necessary prerequisites for good communication among different fracture groups. Instead, the rock types present relatively great anisotropy from the point of view of aquiferous properties.

The rock types along the Kymmen tunnel differ with regard to their aquiferous qualities. Granite gneiss is mostly dry. The more complex sections of granite gneiss and amphibolite present dampness of < 35%, while the corresponding figure for leptite is > 50%.

The frequency of major leakage ($\geq \overset{V}{V}$) in leptite found is more than twice that found in granite gneiss with amphibolite plates. The frequency of major leakage ($\geq \overset{V}{V}$) in granite gneiss with amphibolite plates found is, in turn, more than twice that found in granite gneiss (Palmqvist & Stanfors 1987).

This type of water distribution may partly be attributable to the fact that leptite is more brittle than the other rock types and partly to the absence of filling material in the leptite fractures. The more extensive leakage in granite gneiss with amphibolite plates in comparison with granite gneiss may be attributable to inhomogeneous qualities and fracture formations along the planes of schistosity associated with these qualities.

In the Saltsjö tunnel there is a difference in frequency of visible leakage between the different rock types. More extensive leakage is present in red granite than in grey granite. There are too few occurrences of amphibolite and pegmatite inclusions for the values to be comparable. It is, however, clear that they are far more aquiferous than the surrounding rock, especially at the contact surfaces (Palmqvist & Lindström 1988).

5.6 AQUIFEROUS QUALITIES IN TECTONIC ZONES

As described in chapter 4, there are major differences in the aquiferous qualities of different types of tectonic zones.

In tectonic zones of a regional nature, the structure is generally complex, with crushed sections and sections where there is mineral alteration, alternating with blocky fractured sections, which are sometimes highly aquiferous. The Singö fault zone at the SFR tunnel is approximately 200 m wide, and may be described as a steep shear zone, subjected to repeated deformations. The hydraulic conductivity of the zone is between 10^{-5} and 10^{-7} m/s. The aquiferous qualities within the zone are very unevenly distributed, so that one half of the zone is dry, while all water bearing is concentrated to the other half. The Singö fault zone, the direction of which is N55°W presents, from the southwest, an approximately 40 m wide peripheral zone with somewhat crushed and weathered rock. This is followed by approximately 10 m of crushed and weathered rock. The widest part of the Singö fault zone comprises some 90 - 100 m of slated (highly schistose), altered and somewhat weathered rock. A zone with crushed rock in the direction N70°W has been found within the slated zone. The hydraulic conductivity of the dominant tectonic zones outside and under the SFR tunnel is between 10^{-6} and 10^{-8} m/s (Carlsson & Christiansson 1988).

Gently dipping overthrust zones often present highly aquiferous qualities in the transition section to the hanging wall. One such example is the "Finnsjö" zone, a complexly built zone about 100 m thick. In its uppermost section, this zone presents highly aquiferous qualities, with a hydraulic conductivity of between 10^{-5} and 10^{-6} m/s (water injection tests measured in 20 m sections). Towards the bottom of the zone there are several alternating narrow intervals with very high hydraulic conductivity, more than 10^{-4} m/s measured in 20 m sections. These conductive intervals are separated by bedrock with low hydraulic conductivity.

Below the zone the conductivity in general is low, 10^{-10} to 10^{-9} m/s, but several small sections with high conductivity still occur (Ahlbom & Tirén 1989).

Semiregional and local fracture and crush zones are also clearly decisive with regard to the aquiferous properties of the bedrock. There are, however, major differences in aquiferous qualities from zone to zone. These are dependent on the degree of crushing, whether or not there is fracture filling, the fracture characteristics, etc.

According to Palmqvist & Stanfors (1987), the main inflow in the Kymmen tunnel is in zones in leptite. There is particularly increased inflow in zones of slaty and thin-slaty cleavage. There is only actual clay alteration at the contact surfaces between amphibolite and other rock types.

Most of the zones are parallel with the plane of schistosity, and there is often leakage in fractures parallel with the plane of schistosity. However, within these zones, there is also leakage at the points of intersection with fractures in other directions.

Leakage within the zones is clearly primarily point leakage along the fractures or at the intersection between two fractures.

In the Saltsjö tunnel, too, the tectonic zones are highly decisive with regard to the aquiferous qualities of the bedrock. However, it was not possible to determine any simple relationship between the degree of crushing and water inflow. There are different degrees of clay alteration in the tectonic zones. Since these zones were pregrouted, it is difficult to determine the significance of clay alteration with regard to the aquiferous properties (Palmqvist & Lindström 1988).

In the Göteborg tunnels, increased fracturing in the rock mass in the form of fracture or crush zones along the schistosity generally indicates a significant increase of inflow. These sections also required full front pregrouting, requiring distinctly increased amounts of cement in comparison with the bedrock between these zones. (Palmqvist 1983, Palmqvist & Lindström 1988).

5.7 AQUIFEROUS QUALITIES OUTSIDE TECTONIC ZONES

Between the tectonic zones, the rock mass presents a pattern with one or more fracture groups. The more fracture groups there are, the greater the opportunity for aquiferous flow paths.

Carlsson & Olsson (1977) found that the water inflow in the Forsmark tunnel appears to follow particular patterns in relation to the fissure groups and fissure systems. They also found a correlation between inflow and tectonic influence. Considerable crushing tends to correspond to significant flow volumes.

These connections between water inflow and fissure patterns have made it possible to classify the occurrence of the leakage in relation to each single water-bearing fissure. Five types of leakage have emerged from the observations as dominating the water inflow. The principal feature of each type and the consequent differences among the types are illustrated schematically in figure 5.7.1. The characteristic features of the five types are as follows:

1. Leakage concentrated in apertures in an otherwise tight fissure. This condition mainly occurs in horizontal joints in the gneiss granite.

2. Water inflow occurs along horizontal or medium-steep fissures, often as a distinct flow without noticeable apertures.

3. Water leakage occurs in steep fissures, generally as distinct inflows at a lower boundary of the fissure or on the tunnelfloor.

4. Distinct inflows at intersections between two or more fissures. Generally, no inflows or only very small ones occur along the individual joint planes outside the points of intersection.

5. Water leakage occurs as diffuse inflows, or flows out of the rock on a broad front. In general, no distinction between different inflows is noticeable, and no correspondence between a certain water inflow and a certain fissure can be found.

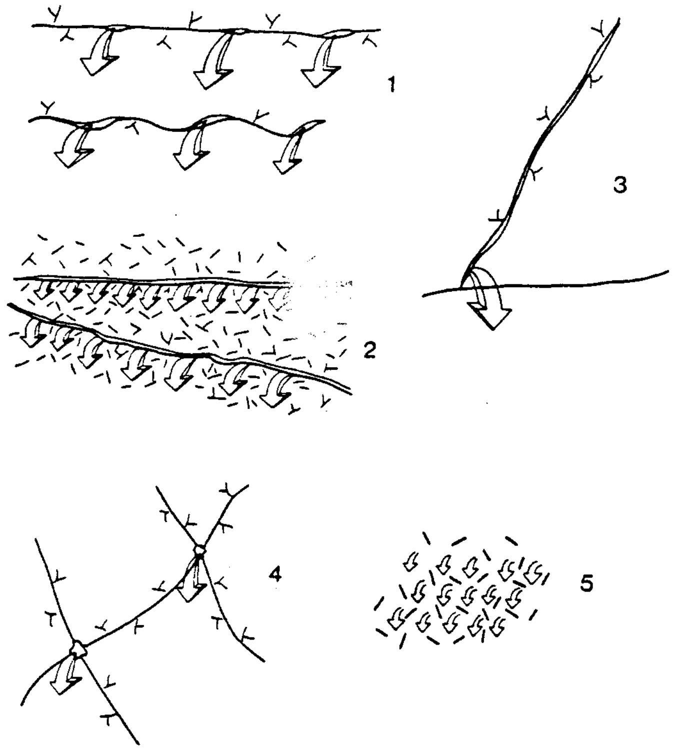


Figure 5.7.1 Schematic illustration of the different appearances of the water inflows (Carlsson & Olsson 1977). 1. Aperture in a horizontal fissure. 2. The inflow along a horizontal or medium-steep fissure with no apertures, but often distinct. 3. Inflow at the lower boundary of a steep fissure. 4. Inflow at the intersection of fissures. 5. Diffuse water inflow.

"One of these types of leakage usually predominates in the inflow pattern in different parts along the tunnel. In most parts however, all the five types of leakage may be found. In the Forsmark tunnel the leakage types in which the water inflow is related to apertures or local widening of the fissures normally have the largest flow volumes. Hence, the first and fourth of the five types, which both satisfy this condition, have the largest volumes for the individual fissures. The occurrence of leakage of type 1, apertures in horizontal fissures, is usually caused by dilation and widenings due to movements at the joint planes. For the fourth type, the water inflow is related to the crossing-points between fissures, and the widening is due to crushing of the rock. Water leakage of type 4 gives rise to the highest total volume. But this condition is not dependent on the quality of the individual fissures but mainly on the fact that type 4 is very common in the four tectonic zones of weakness, where the frequency of fissures and thereby the frequency of crossing-points is high. The capacities of the individual fissures are as high in type 1 as in type 4.

Generally, only small leakage volumes are due to inflows of type 3, water inflows in steep fissures.

Types 1, 2 and 5 are responsible for a great deal of the total inflow to the tunnel. For the individual fissures in these types, the capacities vary within wide limits, from almost nothing to considerable flow volumes." (Carlsson & Olsson 1977).

In the roof of the storage area in SFR some 10,000 fractures have been mapped. Approximately 600 of these are aquiferous. Most of them (two-thirds) are steep. Leakage there was described in terms of six types, according to appearance and behavior. In addition to the types described in figure 5.7.1, a variant of type four has been noted, as well as one completely new type (type six) (Christiansson & Bolvede 1987). The supple-mentary leakage types are described in figure 5.7.2.

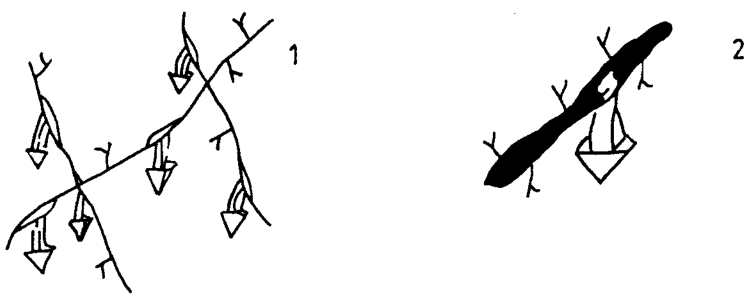


Figure 5.7.2 Aquiferous fracture types in SFR in addition to those described in figure 5.7.1.

1. (type 4) Intersecting fractures with leakage in and around the point of intersection.
2. (type 6) Point leakage. Pockets or cavities (e.g. where the clay has been washed out) (adapted from Christiansson & Bolvede 1987).

Of the aquiferous fractures, approximately 25% have some sort of filling material.

The largest inflows in the storage area also come out of the fractures containing fracture filling material. The most common fracture filling materials are calcite and/or laumontite. Fractures along the plane of schistosity are mostly aquiferous where they occur at greater than ordinary frequency (rock with slaty cleavage).

Water inflow has been noted in 60% of the clay-bearing fractures. Water tends to come out of cavities and in larger quantities in these fractures than in others.

Approximately 20% of the chlorite-bearing fractures are aquiferous. This is particularly evident in conjunction with gently dipping chlorite-filled fractures.

Twelve percent of the fractures filled with laumontite and/or calcite are aquiferous. These fractures are often aquiferous along longer sections of the fractures (Christiansson & Bolvede 1987).

In the Kymmen tunnel, water leakage occurs as point leakage (flow path formations) as well as in leaks along fractures (drapery form). The number of point leaks $\geq \overset{\vee}{\vee}$ per meter tunnel outside tectonic zones is less than one-fifth of the corresponding figure for tectonic zones. The corresponding figure for drapery leakage outside crush zones is about one-fourth of the corresponding figure for tectonic zones. The greatest leakage occurs at the points of intersection between fractures.

Point leakage occurs both along individual fractures and at the points of intersection between different fractures. This leakage often occurs in fractures along the plane of schistosity or in fractures in the contact between amphibolite and the surrounding rock. The leakage in these fractures may occur along a long section of the fractures.

Coherent leakage (drapery leakage) occurs along fractures in different directions, both gently dipping and steeper ones.

Fracture filling (clay, calcite, chlorite, quartz) is of such minor significance that any effect it might have on aquiferous qualities would be negligible (Palmqvist & Stanfors 1987).

In the Saltsjö tunnel horizontal fractures are usually aquiferous. Leakage often occurs at the points of intersection between horizontal fractures and other fracture directions (Palmqvist & Lindström 1988).

Lundström & Rybäck (1989) state, on the basis of their extensive study along the Saltsjö tunnel, that more than 95% of the aquiferous discontinuities are individual fractures. Almost half of the aquiferous fractures are gently dipping, mostly at angles of between 5° and 15°. The horizontal aquiferous fractures are generally (approximately 85%) in the main fracture direction, which is nearly parallel with the tunnel.

More than three-quarters of the aquiferous fractures are long fractures, which may be followed throughout the tunnel section, although there are also shorter aquiferous fractures. These are often found together with one or more long fractures. However, there are occasional short, leaking fractures which have no visible connection with other discontinuities (Lundström & Rybäck 1989).

Lundström & Rybäck (1989) describe the different characteristics of the visible types of leakage. Water may flow out of an entire fracture aperture and/or flow (drip) out of the points of intersection between different fractures. Sometimes there is a channel-shaped flow of water in one fracture.

Calcite is a very common type of fracture filling material. However, mineralization occurs to different extends in different fractures. The calcite in the fractures is resistent to solution. At several places along the tunnel there occur thin streams of water, often occurring in short, calcite-filled fractures. This suggests that there may be flow paths in the calcite-filled fractures where there is a sufficient flow of ground water to prevent the crystallization of calcite (Lundström & Rybäck 1989).

Most of the leakage in the Göteborg tunnels is point leakage.

5.8 REGIONAL SIMILARITIES AND DIFFERENCES

The bedrock studied here represent a number of geological regions. Each region has its own unique conditions with regard to its geological-tectonic history, i.e. the development of rock types, tectonic influence in ductile and ruptural phases, mineral conversion, development of fracture filling minerals, etc. These conditions, in conjunction with the prevailing rock stress situation, provide the background to the presence of water in the rock mass today.

It must be borne in mind, when comparisons are made among the different regions, that the documentation of the presence of water in the different rock constructions was carried out with different objectives and in varying amounts of detail. The documentation methods used must be taken into consideration.

The documentation for each individual tunnel indicates that fracture systems in more acidic, brittle rock types are more aquiferous. When comparisons are made among similar rock types, it is found that the degree of tectonic influence is considerably more decisive with regard to aquiferous qualities than the composition of the bedrock. Other significant parameters are the type and extent of fracture filling, the rock stress situation, and the thickness of the rock overburden.

The general pattern, which is found in each of the rock constructions documented here, is characterized by increased aquiferous qualities where there is increased fracturing in the rock mass. Although this pattern is seen most distinctly in fracture and crush zones, it can often be found in the fracture groups and fracture systems which occur. Fractures along which there have been obvious movements generally present a larger amount of, and more extensive, leakage than other fractures. This is seen clearly as a special case in fractures developing along the contact surfaces between rock types.

In periods of stress in the bedrock, these have become planes of weakness along which fractures have developed and movement has taken place.

6. HYDROGEOLOGICAL INVESTIGATIONS FOR MODELLING

6.1 INTRODUCTION

In chapters 4 and 5, the documented information on the presence of water in different rock types, fractures and fracture and crush zones is presented. In all the constructions included here, actual water bearing has been found to occur in flow paths of varying widths along or at the points of intersection between fracture planes. Irrespective of who documented the size and scope of the water inflow, a general pattern of path flow was found. Different types of leakage were, however, found to dominate at different constructions. The distribution of the flow paths in the bedrock was consistently found to be extremely uneven. Fracture and crush zones both with many flow paths and with large flow paths alternate with virtually impermeable sections of bedrock presenting only a few small flow paths. Locally, in these more impermeable sections, individual fractures however present one or more flow paths with relatively great water flow. Primarily open fractures may, depending on the fracture filling material occurring, be completely impermeable or present individual flow paths, sometimes with considerable water flow.

The picture of the presence of water in the bedrock described above indicates that drill hole examinations, including hydraulic tests, etc., give a highly incomplete picture of the flow path development in the rock and its aquiferous qualities. Hydraulic tests, test pumping, etc. can only give a reasonably exact picture of the tectonic development of the zone, its fracture characteristics, aquiferous properties, etc. when drilling takes place through fracture or crush zones the existence of which have been proven using other methods. In the rock mass between actual fracture or crush zones, a drill hole gives what may only be considered arbitrary information. Hydraulic tests and test pumping in this type of hole may, in the best case, give information as to the mean aquiferous qualities of the bedrock, but provide no details as to the flow paths and their characteristics. Proof of this may, among other indications, be found in the information from tunnels in urban areas where the driving was preceded by extensive pregrouting. In such cases, a large number of grouting holes are often drilled, at distances of less than 1 m apart. Great differences in aquiferous properties are found in different holes, with apparently only minor differences in hydraulic characteristics between different fractures and fracture zones, and even in highly homogeneous sections of bedrock. Many of these holes are completely impermeable, and only to a very small extent can adjacent drill holes be found to correspond. Thus there is great uncertainty as to how well one drill hole describes the aquiferous properties of any given section of bedrock. How many drill holes would be required for satisfactory certainty?

6.2 BASIS FOR MODELLING A SECTION OF BEDROCK

In consideration of the difficulties described above, it is essential that collection of factual information on the flow path development of a rock mass and its aquiferous qualities be carried out systematically, with regard to the petrographic and tectonic composition of the bedrock. Once a detailed model of expectation has been drawn up, an assessment of flow path development may be made on the basis of the documentation on the presence of water presented in chapters 4 and 5.

This model of expectation must, consequently, include the composition of the bedrock, and its degrees of homogeneity and anisotropy. It must also provide information as to the general tensile properties of the rock types, as well as the characteristics and, if possible, the genesis of both fracture groups and fracture or cross zones. Important supplementary information includes the extent and type of fracture filling, and the prevailing rock stress conditions.

On the basis of the model of expectation as described above, a probable general pattern of flow path development and aquiferous properties may be projected, taking into consideration the degree of tectonization, and the consequent movements along the fracture planes and in the fracture and crush zones. A systematic investigation of fracture and crush zones as well as the fracture groups occurring, carried out with the aid of appropriately directed core holes, then makes it possible to verify and supplement the model of flow path development. A number of core holes will probably be required for each zone or fracture group, to penetrate the zone both at different horizontal points and at different depths, in order to determine the variations in aquiferous properties in each object being studied. With the aid of oriented drill cores, detailed data with regard to where the water flows into the drill hole (spinner tests) may be determined for the relevant fracture group.

In conjunction with tunnel driving in the area investigated, the predictive flow-path model can be verified and supplemented. This requires, however, that the driving of the tunnels be carried out as cautiously as possible, so that the leakage picture not be too considerably disturbed by the blasting.

Subsequent to supplementing and, if necessary, revising the flow-path model, prediction and modelling with regard to deeper sections of the bedrock may be carried out. These predictions may later be compared with data from, for example deep drill holes and test pumping.

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SKB Annual Report 1988
Including Summaries of Technical Reports Issued during 1988
Stockholm, May 1989

Technical Reports

List of SKB Technical Reports 1990

TR 90-01
FARF31 –
A far field radionuclide migration code for use with the PROPER package
Sven Norman[1], Nils Kjellbert[2]
[1] Starprog AB
[2] SKB AB
January 1990

TR 90-02
Source terms, isolation and radiological consequences of carbon-14 waste in the Swedish SFR repository
Rolf Hesböl, Ignasi Puigdomenech, Sverker Evans
Studsvik Nuclear
January 1990

TR 90-03
Uncertainties in repository performance from spatial variability of hydraulic conductivities –
Statistical estimation and stochastic simulation using PROPER
Lars Lovius[1], Sven Norman[1], Nils Kjellbert[2]
[1] Starprog AB
[2] SKB AB
February 1990

TR 90-04
Examination of the surface deposit on an irradiated PWR fuel specimen subjected to corrosion in deionized water
R.S. Forsyth, U-B. Eklund, O. Mattsson, D. Schrire
Studsvik Nuclear
March 1990

TR 90-05
Potential effects of bacteria on radionuclide transport from a Swedish high level nuclear waste repository
Karsten Pedersen
University of Gothenburg, Department of General and Marine Microbiology, Gothenburg
January 1990

TR 90-06
Transport of actinides and Tc through a bentonite backfill containing small quantities of iron, copper or minerals in inert atmosphere
Yngve Albinsson, Birgit Sätmark, Ingemar Engkvist, W. Johansson
Department of Nuclear Chemistry, Chalmers University of Technology, Gothenburg
April 1990

TR 90-07
Examination of reaction products on the surface of UO_2 fuel exposed to reactor coolant water during power operation
R S Forsyth, T J Jonsson, O Mattsson
Studsvik Nuclear
March 1990

TR 90-08
Radiolytically induced oxidative dissolution of spent nuclear fuel
Lars Werme[1], Patrik Sellin[1], Roy Forsyth[2]
[1] Swedish Nuclear Fuel and waste Management Co (SKB)
[2] Studsvik Nuclear
May 1990

TR 90-09
Individual radiation doses from unit releases of long lived radionuclides
Ulla Bergström, Sture Nordlinder
Studsvik Nuclear
April 1990

TR 90-10
Outline of regional geology, mineralogy and geochemistry, Poços de Caldas, Minas Gerais, Brazil
H D Schorscher[1], M E Shea[2]
[1] University of Sao Paulo
[2] Battelle, Chicago
December 1990

TR 90-11
Mineralogy, petrology and geochemistry of the Poços de Caldas analogue study sites, Minas Gerais, Brazil.
I: Osamu Utsumi uranium mine
N Waber[1], H D Schorscher[2], A B MacKenzie[3], T Peters[1]
[1] University of Bern
[2] University of Sao Paulo
[3] Scottish Universities Research & Reactor Centre (SURRC), Glasgow
December 1990

TR 90-12
Mineralogy, petrology and geochemistry of the Poços de Caldas analogue study sites, Minas Gerais, Brazil.
II: Morro do Ferro
N Waber
University of Bern
December 1990

TR 90-13
Isotopic geochemical characterisation of selected nepheline syenites and phonolites from the Poços de Caldas alkaline complex, Minas Gerais, Brazil
M E Shea
Battelle, Chicago
December 1990

TR 90-14
Geomorphological and hydrogeological features of the Poços de Caldas caldera, and the Osamu Utsumi mine and Morro do Ferro analogue study sites, Brazil
D C Holmes[1], A E Pitty[2], R Noy[1]
[1] British Geological Survey, Keyworth
[2] INTERRA/ECL, Leicestershire, UK
December 1990

TR 90-15
Chemical and isotopic composition of groundwaters and their seasonal variability at the Osamu Utsumi and Morro do Ferro analogue study sites, Poços de Caldas, Brazil
D K Nordstrom[1], J A T Smellie[2], M Wolf[3]
[1] US Geological Survey, Menlo Park
[2] Conterra AB, Uppsala
[3] Gesellschaft für Strahlen- und Umweltforschung (GSF), Munich
December 1990

TR 90-16
Natural radionuclide and stable element studies of rock samples from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil
A B MacKenzie[1], P Linsalata[2], N Miekeley[3], J K Osmond[4], D B Curtis[5]
[1] Scottis Universities Research & Reactor Centre (SURRC), Glasgow
[2] New York Medical Centre
[3] Catholic University of Rio de Janeiro (PUC)
[4] Florida State University
[5] Los Alamos National Laboratory
December 1990

TR 90-17
Natural series nuclide and rare earth element geochemistry of waters from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil
N Miekeley[1], O Coutinho de Jesus[1], C-L Porto da Silveira[1], P Linsalata[2], J N Andrews[3], J K Osmond[4]
[1] Catholic University of Rio de Janeiro (PUC)
[2] New York Medical Centre
[3] University of Bath
[4] Florida State University
December 1990

TR 90-18
Chemical and physical characterisation of suspended particles and colloids in waters from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil
N Miekeley[1], O Coutinho de Jesus[1], C-L Porto da Silveira[1], C Degueldre[2]
[1] Catholic University of Rio de Janeiro (PUC)
[2] PSI, Villingen, Switzerland
December 1990

TR 90-19
Microbiological analysis at the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil
J West[1], A Vialta[2], I G McKinley[3]
[1] British Geological Survey, Keyworth
[2] Uranio do Brasil, Poços de Caldas
[3] NAGRA, Baden, Sitzerland
December 1990

TR 90-20
Testing of geochemical models in the Poços de Caldas analogue study
J Bruno[1], J E Cross[2], J Eikenberg[3], I G McKinley[4], D Read[5], A Sandino[1], P Sellin[6]
[1] Royal Institute of Technology (KTH), Stockholm
[2] AERE, Harwell, UK
[3] PSI, Villingen, Switzerland
[4] NAGRA, Baden, Switzerland
[5] Atkins ES, Epsom, UK
[6] Swedish Nuclear and Waste Management Co (SKB), Stockholm
December 1990

TR 90-21
Testing models of redox front migration and geochemistry at the Osamu Utsumi mine and Morro do Ferro analogue sites, Poços de Caldas, Brazil
J Cross[1], A Haworth[1], P C Lichtner[2], A B MacKenzi[3], L Moreno[4], I Neretnieks[4], D K Nordstrom[5], D Read[6], L Romero[4], S M Sharland[1], C J Tweed[1]
[1] AERE, Harwell, UK
[2] University of Bern
[3] Scottish Universities Research & Reactor Centre (SURRC), Glasgow
[4] Royal Institute of Technology (KTH), Stockholm
[5] US Geological Survey, Menlo Park
[6] Atkins ES, Epsom, UK
December 1990

TR 90-22
Near-field high temperature transport: Evidence from the genesis of the Osamu Utsumi uranium mine analogue site, Poços de Caldas, Brazil
L M Cathles[1], M E Shea[2]
[1] University of Cornell, New York
[2] Battelle, Chicago
December 1990

TR 90-23
Geochemical modelling of water-rock interactions at the Osamu Utsumi mine and Morro do Ferro analogue sites, Poços de Caldas, Brazil
D K Nordstrom[1], I Puigdomenech[2], R H McNutt[3]
[1] US Geological Survey, Menlo Park
[2] Studsvik Nuclear, Sweden
[3] McMaster University, Ontario, Canada
December 1990

TR 90-24
The Poços de Caldas Project: Summary and implications for radioactive waste management
N A Chapman[1], I G McKinley[2], M E Shea[3], J A T Smellie[4]
[1] INTERRA/ECL, Leicestershire, UK
[2] NAGRA, Baden, Switzerland
[3] Battelle, Chicago
[4] Conterra AB, Uppsala

TR 90-25
Kinetics of UO_2(s) dissolution reducing conditions: numerical modelling
I Puigdomenech[1], I Cass[2], J Bruno[3]
[1] Studsvik AB, Nyköping, Sweden
[2] Department of Chemical Engineering, E.T.S.E.I.B. (U.P.C.), Barcelona, Spain
[3] Department of Inorganic Chemistry, The Royal Institute of Technology, Stockholm, Sweden
May 1990

TR 90-26
The effect from the number of cells, pH and lanthanide concentration on the sorption of promethium on gramnegative bacterium (Shewanella Putrefaciens)
Karsten Pedersen[1], Yngve Albinsson[2]
[1] University of Göteborg, Department of General and Marine Microbiology, Gothenburg, Sweden
[2] Chalmers University of Technology, Department of Nuclear Chemistry, Gothenburg, Sweden
June 1990

TR 90-27
Isolation and characterization of humics from natural waters
B Allard[1], I Arsenie[1], H Borén[1], J Ephraim[1], G Gårdhammar[2], C Pettersson[1]
[1] Department of Water and Environmental Studies, Linköping University, Linköping, Sweden
[2] Department of Chemistry, Linköping University, Linköping, Sweden
May 1990

TR 90-28
Complex forming properties of natural organic acids. Part 2. Complexes with iron and calcium
James H Ephraim[1], Andrew S Mathuthu[2], Jacob A Marinsky[3]
[1] Department of Water in Environment and Society, Linköping University, Linköping, Sweden
[2] Chemistry department, University of Zimbabwe, Harare, Zimbabwe
[3] Chemistry Department, State University of New York at Buffalo, Buffalo, NY, USA
July 1990

TR 90-29
Characterization of humic substances from deep groundwaters in granitic bedrock in Sweden
C Pettersson, J Ephraim, B Allard, H Borén
Department of Water and Environmental Studies, Linköping University, Linköping, Sweden
June 1990

TR 90-30
The earthquakes of the Baltic shield
Ragnar Slunga
Swedish National Defence Research Institute
June 1990

TR 90-31
Near-field performance of the advanced cold process canister
Lars Werme
Swedish Nuclear Fuel and Waste Management Co (SKB)
September 1990

TR 90-32
Radioclide transport paths in the nearfield – a KBS-3 concept study
Roland Pusch
Clay Technology AB and Lund University of Technology
July 1990

TR 90-33
PLAN 90
Costs for management of the radioactive waste from nuclear power production
Swedish Nuclear Fuel and Waste Management Co (SKB)
June 1990

TR 90-34
GEOTAB: User's guide – Version 1.8.2
Ergodata
October 1990

TR 90-35
Dose conversion factors for major nuclides within high level waste
Ulla Bergström, Sture Nordlinder
Studsvik Nuclear
November 1990

TR 90-36
Sensitivity analysis of groundwater flow Licentiate thesis
Yung-Bing Bao
Royal Institute of Technology, Department of Land and Water Resources, Stockholm, Sweden
December 1990

TR 30-37
The influence of fracture mineral/ groundwater interaction on the mobility of U, Th, REE and other trace elements
Ove Landström[1], Eva-Lena Tullborg[2]
[1] Studsvik AB, Nyköping
[2] SGAB, Gothenburg
December 1990

TR 90-38
Solute transport in fracture rock – Applications to radionuclide waste repositories
Ivars Neretnieks
Department of Chemical Engineering,
Royal Institute of Technology, Stockholm
December 1990

TR 90-39
Modelling of the movement of the redox front in the uranium mine in Poços de Caldas, Brazil
Leonardo Romero, Luis Moreno, Ivars Neretnieks
Royal Institute of Technology, Stockholm
June 1990

TR 90-40
Distinct element modelling of the rock mass response to glaciation at Finnsjön, Central Sweden
Lars Rosengren[1], Ove Stephansson[2]
[1] Itasca Geomekanik AB, Falun, Sweden
[2] Division of Rock Mechanics, Luleå University of Technology, Luleå, Sweden
December 1990