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Forsmark site investigation

Investigations of superficial fracturing and block displacements at drill site 5

Bengt Leijon (ed)
Svensk Kärnbränslehantering AB

December 2005

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

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Preface

This report presents results and conclusions from a series of investigations conducted at drill site 5 at Forsmark, Sweden. The work was decided and organized, on short notice, during October and November 2003 as a consequence of unexpected findings following disclosure of the rock surface at the drill site – the state of fracturing of the superficial rock exhibited clear traces of glacial- or postglacial impact. The investigations launched were aimed at documenting the conditions observed, hopefully shed some light on their causes, and provide a basis for assessing possible implications on the merits of the Forsmark site for a deep repository.

Chapters 1 through 6 of the report have been compiled by SKB. They provide the background and scope of the investigations, summarize their results and present conclusions drawn. The remainder of the report comprises seven appendices, each constituting the documentation of a contribution to the investigation program carried out. The appendices should be seen as “stand-alone” reports, although certain background information is shared and some cross references are found. Results, viewpoints and conclusions presented in the appendices are those of their respective authors.

Summary

Removal of the soil cover during preparation of drill site 5 at Forsmark revealed unexpected conditions at the bedrock surface. This included partly heavy fracturing, sediment fillings in several large-aperture fractures and associated dislocations of blocks. There were also abundant examples of angular blocks with edges virtually free from signs of glacial abrasion.

It was preliminary concluded that the anomalous conditions were, somehow and to some extent, a result of fracturing and/or reactivation under glacial- or postglacial conditions. Depending on origin, such phenomena may or may not have serious implications with respect to overall site suitability for a deep repository. It was therefore decided to conduct a series of investigations at drill site 5 in order to document the conditions in more detail and hopefully contribute some insight into their geological background. The ambition was also to provide a basis for assessing possible implications on the merits of the Forsmark site for a deep repository. Investigations covered the overburden and bedrock surface at the site, as well as the subsurface rock down to a depth of about 130 m.

Detailed mapping of the rock surface verified an excessive portion of open fractures, as compared to other sites at Forsmark. Most of these open fractures exhibited signs of either formation or reactivation under late- or postglacial conditions, although judgements in this respect were in many cases uncertain. The most striking features documented were a number of predominant fractures striking mainly NE-SW and dipping gently to the SE. These fractures had apertures ranging up to about 20 cm and were typically filled with unconsolidated sediments. The overlying rock blocks appeared uplifted and were in some cases slightly rotated relative to the underlying bedrock. Investigations of the filling material revealed a composition resembling that of the till overburden and indicated that sediment-bearing water has been flowing into the fractures, followed by quiet sedimentation of the material.

The subsurface investigations entailed ground penetrating radar surveying and percussion drilling of inclined boreholes to penetrate the rock below the site. The key objective was to determine whether the disturbances observed at surface persisted towards depth. Drilling verified the presence of anomalously wide and sediment-filled fractures, but only to a few metres depth. Below about 5 – or at most 10 – metres depth, there were no signs of conditions deviating from those typically encountered within the tectonic lens at Forsmark. Based on these observations, it was concluded that the disturbances observed are surface-related phenomena confined to the superficial rock.

Investigation results unambiguously support the preliminary conclusion that the surface bedrock has been subject to fracturing and fracture reactivation in late- or postglacial time. Interpretations of the underlying causes and mechanisms, however, remain speculative. A probable explanation for the major, sediment-filled fractures is that they are so-called sheet structures. This explanation is supported not only by the present data from drill site 5, but also by comprehensive investigations of in all respect similar phenomena observed in connection with the construction of the nuclear power facilities at Forsmark in the 1970's. Sheet structures are basically formed by vertical extension generated by high horizontal stresses. Provided that the rock can accumulate sufficiently large amounts of recoverable strain energy upon loading, the failure process may be accompanied by sudden energy release, causing progressive and more or less "explosive" failures. The extreme fracture

apertures and general distortion of the surface rock at drill site 5 can possibly be attributed to such violent failures. Analogous phenomena can be observed in tunnels in brittle rock, when stresses parallel to the tunnel periphery exceed the strength of the rock, resulting in sudden spalling failures.

As regards the important question of possible implications on site suitability for a repository, no implications on conditions at repository depth, i.e. within the interval 400–700 m, can be foreseen. This is so because the disturbances are interpreted to be 1) confined to uppermost few metres of rock; 2) consequences of events that are as such conditioned by the proximity to the ground surface. They will, however, obviously hamper the use of surface- and shallow-depth data for predicting conditions at depth. This can have considerable implications on investigation methodology and site assessment.

Sammanfattning

När jordtäcket vid borrplats 5 i Forsmark avrymdes konstaterades oväntade förhållanden i den blottade bergytan. Ytberget var uppsprucket och ett flertal stora sprickor fyllda med jordliknande material observerades. Det fanns också talrika exempel på förskjutningar i sprickplan som hade resulterat i skarpkantade block som tycktes ha undgått glacial avslipning.

Den preliminära slutsatsen var att bergytan utsatts för någon form av uppsprickning och/eller reaktivering under glaciala- eller postglaciala förhållandena. Beroende på ursprung och tillkomsthistoria kan sådana fenomen ha stor betydelse för platsens lämplighet för ett slutförvar. Mot denna bakgrund beslöts att tillfälligt avbryta arbetena med att förbereda borrplatsen för att istället ge utrymme för en serie undersökningar på platsen. Syftet var att dokumentera förhållandena i detalj och förhoppningsvis kunna förstå den geologiska bakgrunden, för att med detta som grund kunna belysa frågan om eventuell betydelse för Forsmark som kandidatplats för slutförvaret. Undersökningarna omfattade jordtäcket, bergytan och berget ner till cirka 130 m djup.

Detaljerad ytkartering verifierade det omedelbara intrycket att andelen öppna sprickor var väsentligt större än på andra platser i området som karterats på samma sätt. Sprickornas ursprung och ålder var i många fall svåra att bedöma, men flertalet uppvisade tecken på att ha bildats eller reaktiverats under sen- eller postglacial tid. Ett antal dominerande sprickor med flack stupning mot sydost och ungefärlig strykning nordost-sydväst dokumenterades. Dessa sprickor var upp till 20 cm vida och regelmässigt fyllda med sediment. Ytblocken ovanför de flacka sprickorna hade lyfts upp och i en del fall roterats något i förhållande till underliggande berg. Undersökningar av fyllnadsmaterialet påvisade en sammansättning motsvarande den överlagrande moränen. Struktur och sammansättning tolkades som att fyllnadsmaterialet hade transporterats in i sprickorna via strömmande vatten, och där sedimenterat under lugna förhållanden.

Undersökningarna under den synliga bergytan omfattade markradarprofiler över det blottade området samt hammarborrhål, riktade diagonalt under samma område. Huvudsyftet var att avgöra om de anomala förhållandena på ytan hade någon motsvarighet mot djupet. Borrningen påvisade stora, sedimentfyllda sprickor, men bara till några få meters djup. På djup större än cirka 5 m – eller högst 10 m – visade borrhålsdata inte på något som tyder på andra förhållanden än vad som under platsundersökningens gång konstaterats på en rad andra platser inom den tektoniska linsen i Forsmark. Slutsatsen blev därmed att de störningar som kunde konstateras inte hade någon påverkan mot djupet.

Sammantaget stödjer undersökningsresultaten genomgående den preliminära bedömningen att sprickbildning och reaktivering av äldre sprickor i ytberget skett under sen- eller postglaciala förhållanden. Tolkningarna av möjliga mekanismer och händelseförlopp som kan ha åstadkommit denna påverkan förblir emellertid spekulativa. De dominerande, sedimentfyllda flacka sprickorna är i grunden sannolikt så kallade bankningssprickor. Denna tolkning stöds inte bara av data från borrplats 5, utan även av de omfattande undersökningar av i alla avseenden liknande fenomen som gjordes på industriområdet i Forsmark i samband med att kärnkraftverken byggdes på 1970-talet. En möjlig förklaring till de extremt stora sprickvidderna och talrika blockförskjutningarna i ytberget är att uppsprickningen skett progressivt och mer eller mindre explosivt till följd av att ackumulerad töjningsenergi utlösts.

Nödvändiga förutsättningar för ett sådant förlopp är höga horisontella belastningar och att berget, innan brott, kunnat härbärgera ett överskott av återvinningsbar töjningsenergi. Samma typ av explosiva brottförlopp kan observeras i tunnlar i sprött berg, när belastningarna överskrider bergets bärförmåga.

Störningar av den typ som observerades på borrplats 5 bedöms inte kunna ha någon direkt inverkan på bergförhållandena på tänkbara förvarsdjup, det vill säga i intervallet 400–700 m. Skälen är att störningarna tolkas som 1) begränsade till några få meter ytberg; 2) resultat av förlopp som i sig förutsätter närheten till en fri yta. Däremot är det självfallet så att när ytberget har andra egenskaper än berget mot djupet begränsas möjligheterna att nyttja ytinformation för att prediktera förhållanden på djupet. Detta kan ha avsevärd betydelse med avseende på undersökningsmetodik och platsbeskrivning.

Contents

1 Introduction

1.1 Background

The site investigation at Forsmark includes detailed geological documentation of the rock surface at most of the sites for core drilling. Documentation work is performed in connection with site preparation. In order to provide the necessary working conditions for the drilling activities, the superficial soil cover has to be removed over an area of some 20 by 30 m, and replaced by a levelled and compacted gravel fill. To also allow investigation of the rock surface, the excavation work is extended so that the soil cover is removed completely and the rock surface is carefully cleaned.

Thus, site preparation provides an opportunity to document the rock with a minimum of extra effort and environmental impact. This is considered valuable, especially since there is a shortage of naturally occurring rock exposures in the area. Documentation comprises surveying, geological mapping and photography.

The 5th deep cored borehole within the investigation area was sited just west of the northwestern extension of Bolundsfjärden, see Figure 1-1. The location was chosen on the basis of geoscientific data needs and local environmental protection considerations. After construction of an access road, site preparation commenced by removing trees and stripping away the humus layer, followed by excavation of the overburden to uncover the bedrock surface.

Figure 1-2 shows an overview of the site, as it appeared after clearing and surveying of the rock surface. In contrast to the rather flat overburden surface, the rock surface showed a rugged contour. Overburden depths varied from almost zero to the southeast, to about 5 m at the northwestern boundary of the excavation.

It soon became obvious that the superficial rock exhibited anomalous geometrical features, resulting from fracturing and block dislocations. Blocks at the rock surface were displaced, both mutually and relative to the underlying bedrock. Displacements typically ranged in the centimetre-scale, but several examples were seen of dislocations in the decimetre-scale. In many cases, blocks had been formed from originally larger slabs of surface rock by fractures cutting through glacially sculptured surfaces, leaving apparently fresh block edges without any obvious signs of post-displacement glacial erosion. Figure 1-3 shows an illustrative example. The soil cover, as observed in the excavation cuts, did not exhibit any disruptions corresponding to the displacements seen in the superficial rock.

Another observation was that a number of large, gently dipping fractures were filled with soil material, similar in appearance to the excavated till overburden. Thicknesses of these fracture fillings varied up to about 2 dm. Overlying blocks were uplifted correspondingly, and in some cases slightly rotated relative to the underlying rock. Figure 1-4 shows one of these fractures.

It was clear that the surface rock conditions at drill site 5 differed from those at the other drill sites in the area. However, phenomena similar to those seen at drill site 5 have been reported from investigations conducted at Forsmark in the 1970's, in connection with the construction of the nuclear power plant /Carlsson 1979/.

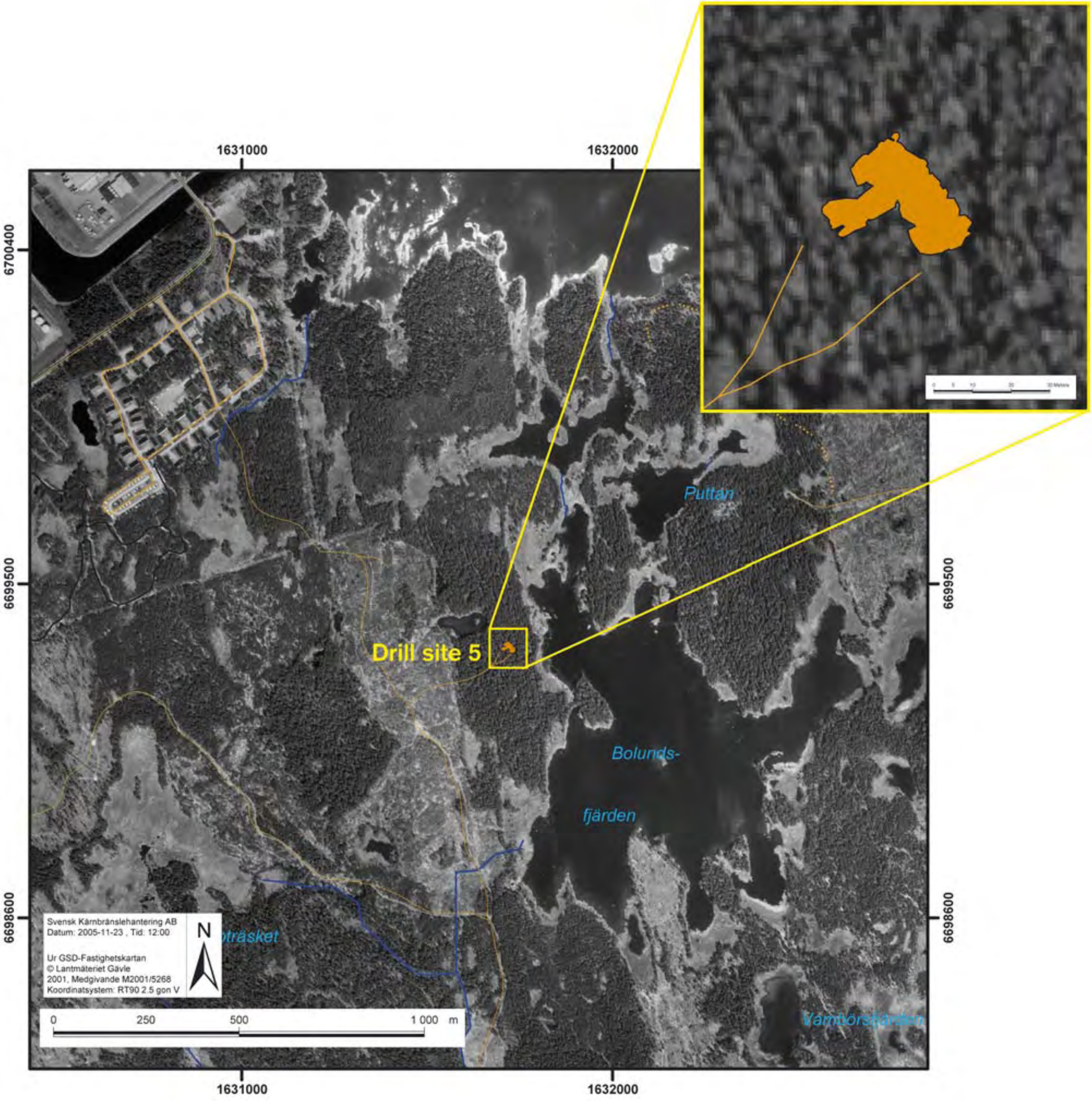

Figure 1-1. *Location of drill site 5 and geometry of the rock exposure.*

1.2 Actions taken

Based on the unexpected field observations and background information, the preliminary assessment was that the rock surface conditions at drill site 5 were, somehow and to some extent, a result of glacial or post-glacial processes. Uncertainty remained, however, regarding the pattern of fracture- and block dislocations. Responsible forces and mechanisms were not understood, although candidates were forces related to ice movement, water pressure gradients, rock stresses, or some combination of these.

Figure 1-2. *Appearance of the bedrock surface at drill site 5 after removal of the overburden. View from the southwest.*

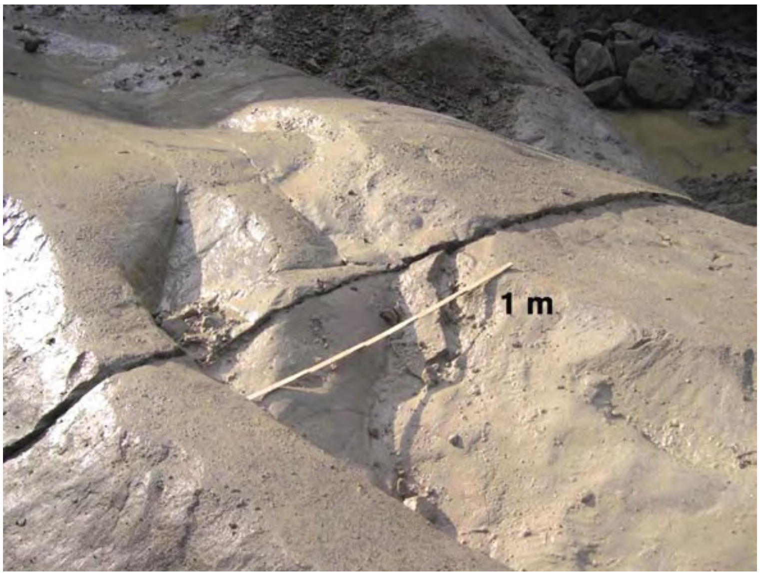

Figure 1-3. *Example of a fracture cutting almost vertically through a large surface block. The originally polished surface is displaced and the resulting block edges do not show any signs of glacial abrasion.*

Figure 1-4. *Example of a gently dipping fracture, more than 10 cm wide and filled with sedimented soil material.*

Provided that the phenomena observed were restricted to the near-surface rock, they would unlikely alter the merits of the site in terms of suitability for a deep repository. They could, however, hamper the use of surface observations to predict rock conditions at depth, probably also the ability to understand and model near-surface conditions and processes. Another possibility that could not be ruled out was that the surface conditions reflected some form of neotectonic activity and/or deformation at depth. If so, this could have serious implications on site suitability.

Thus, the situation at drill site 5 raised important questions such as:

- How can the conditions at drill site 5 be described, quantitatively and in more detail?
- Are the anomalies confined to the superficial rock, or do they reflect disturbances at larger depth?
- What can be learnt from previous studies of similar phenomena?
- What events and mechanisms may have caused the present conditions?
- Are there potential implications on site suitability?

Given these questions, backfilling and other preparation work at the site was temporarily halted in order to identify needs and possibilities for additional investigations with the objective to provide some answers, furnish an investigation programme and carry out the investigations.

2 Investigation programme

Discussions within the group of geoscientific experts involved in the site investigation concluded that investigations should comprise documentation of the soil cover and rock surface at the site, as well as the bedrock beneath the observable surface. Documenting the soil cover was considered important because its composition and structure may contribute to understanding the temporal history of rock displacements. The need for thorough investigation of the exposed rock surface was obvious. Besides standard fracture parameters such as length and orientation, investigation objectives called for special emphasis on fracture displacements and related block movements, indications of fracture origin and relative age, indications of fracture reactivation, level of glacial impact and the characteristics of the sediment infillings found in some fractures. Investigating bedrock conditions below surface, finally, was necessary in order to determine whether anomalous conditions persisted towards depth.

The investigation programme that emerged comprised the following components:

A **Detailed documentation and classification of observable fractures.** A large number of carefully mapped fractures were classified in various respects, and comparisons were made with other sites at Forsmark. The study was conducted by Golder Associates AB and led by Dr Lars Mærsk Hansen.

B **Documentation of glacial sediments, fractures and glacial striae.** This study comprised investigations of both the overburden as exposed in the excavation walls, sediments found in fractures, and the state of fracturing of the rock surface. Emphasis was on understanding the various forms of glacial impact seen at the site. The work was conducted by a team from the Geological Survey of Sweden (Figure 2-1), guided by Mr Robert Lagerbäck.

C **Microfossil analysis.** As part of a larger study, samples taken from both the overburden and sediments in fractures at drill site 5 were analysed with respect to their content of microfossils. The aim was primarily to support study B in terms of interpretation and dating of the sediments. The work was conducted by Dr Ann-Marie Robertsson, Dept of Physical Geography and Quaternary Geology, Stockholm University.

D **Examination of fracture samples.** Thin sections and fracture surfaces sampled from potentially glacial fractures (Figure 2-2) were studied using electron microscopy. The objective was to contribute to understanding of fracture age and history. The work was conduced by Dr Björn Sandström, Earth Science Centre, Gothenburg University and Dr Eva-Lena Tullborg, Terralogica AB.

E **Ground penetration radar survey.** This effort was made because ground penetration radar can provide information on near-surface bedrock conditions. The work was conducted by Malå GeoScience AB.

F **Drilling and borehole investigations.** From a position immediately beside the excavation, two inclined percussion boreholes were drilled below the excavation, to allow the bedrock to be investigated down to c 130 m depth. Borehole logging and testing was performed using a number of methods. The work was integrated into the ongoing percussion drilling program at Forsmark.

Figure 2-1. Geologists from the Geological Survey of Sweden examining the rock surface and filled fractures at drill site 5.

Some of the investigation efforts were coordinated with ongoing work at Forsmark, while others were organized specifically for the present purpose. Table 2-1 provides an overview of the pertinent controlling documents, in the form of activity plans and method descriptions.

Table 2-1. Overview of controlling documents for the investigations at drill site 5.

Investigation	Activity plan	Method description
Detailed documentation and classification of observable fractures	AP PF 400-03-96 and AP PF 400-03-75	MD 132.003
Documentation of glacial sediments, fractures and glacial striae	AP PF 400-03-20	MD 133.001
Microfossil analysis	AP PF 400-03-98	
Examination of fracture samples	AP PF 400-03-96	
Ground penetration radar survey	AP PF 400-03-85	MD 251.003
Drilling and borehole investigations	AP PF 400-03-68 (HFM14), AP PF 400-03-82 (HFM15)	MD 610.003

In addition to the field investigations, the site was visited and examined by a number of experienced experts. One of them was professor Anders Carlsson (Figure 2-3) who conducted the comprehensive investigations of similar phenomena during the period when the power plant at Forsmark was constructed. Another was professor Roland Pusch, who is the author of Appendix G to this report.

The investigation programme was furnished during September 2003 and investigations largely commenced during the following month. On October 29, preliminary results were presented in the form of a seminar held at Forsmark. Participating were representatives from SKB, the organisations responsible for the investigations, KASAM, SKI and SSI. The programme also included a field excursion to drill site 5, see Figure 2-4. It was concluded from the seminar that the investigation programme launched provided a relevant and satisfactory documentation of the site. This applied both when considering the work in terms of input to the site investigation, and in terms of contributing a case study to the geoscientific community at large. Thus, after completing remaining investigation activities, most of the excavation was backfilled and preparation work for the deep core drilling was resumed. This excluded a smaller area, about 8 by 12 m in size towards the more shallow southeastern part of the excavation, where the rock surface was left open to be readily observable also henceforth by geologists and other others interested.

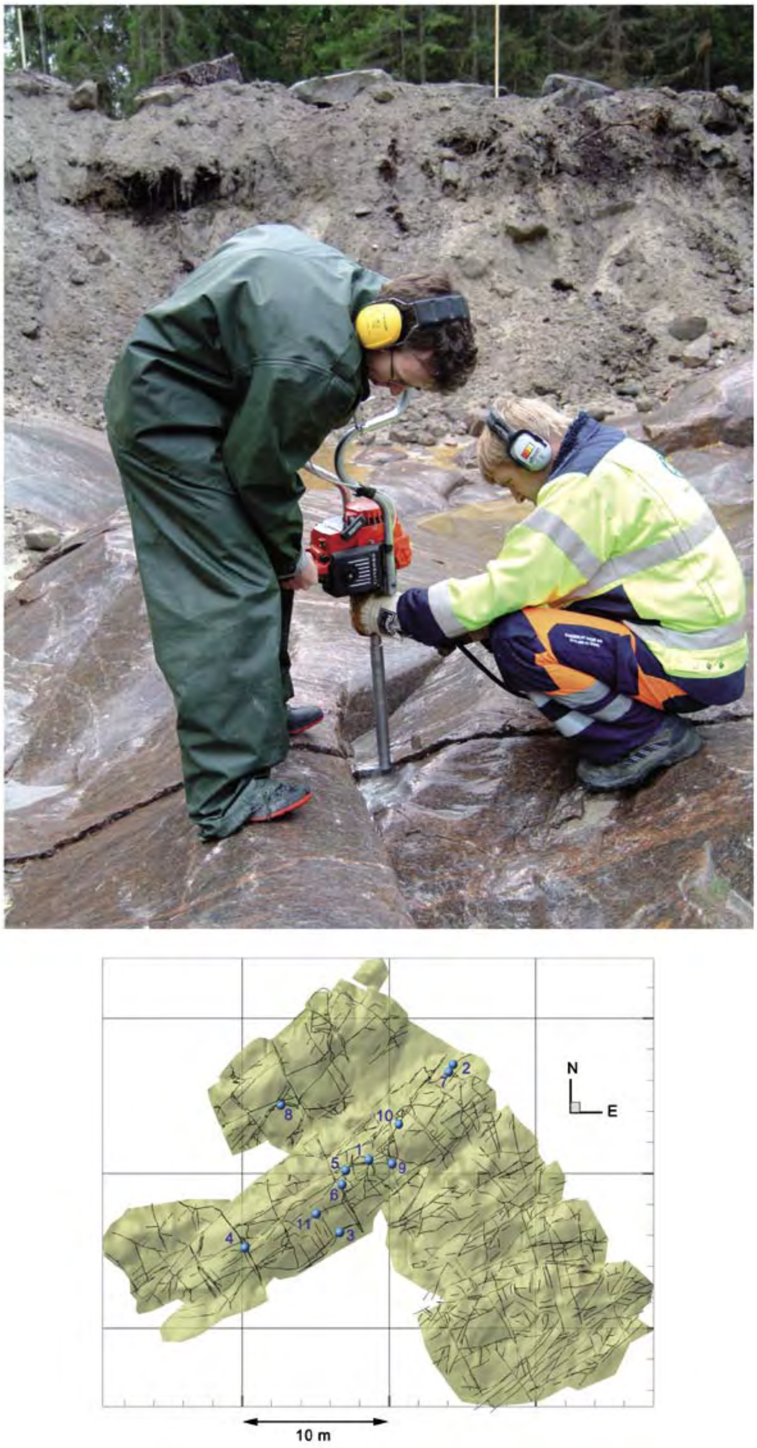

Figure 2-2. *Sampling of fracture surfaces for electron microscopy. Upper: Hand-held drilling to retrieve a small core sample across a fracture. Lower: Sampling points.*

Figure 2-3. *Prof Anders Carlsson (second from left) visiting drill site 5 together with SKB and SGU personnel, November 2003.*

Figure 2-4. *Field excursion to drill site 5 on October 29, 2003. Participants from SKI, SSI, KASAM and SKB being guided by Robert Lagerbäck, Geological Survey of Sweden.*

3 Documentation

The investigations listed above are documented in the form of the following seven appendices to this report:

Appendix A
Description and assessment of glacial fractures at drill site 5, Forsmark
Lars Mærsk Hansen, Isabelle Staub, Jon Vestgård, Ola Forssberg
Golder Associates AB

Appendix B
Documentation of glacial sediments, fractures and glacial striae at drill site 5
Hanna Lokrantz, Joachim Albrecht
Geological Survey of Sweden

Appendix C
Microfossil analyses of samples from sediment filled fractures and till at drill site 5
Ann-Marie Robertsson
Department of Physical Geography and Quaternary Geology, Stockholm University

Appendix D
Descriptions of thin sections and surface samples from near-surface fractures at drill site 5 – samples from short drillcores
Björn Sandström, Earth Science Centre, Göteborg University
Eva-Lena Tullborg, Terralogica AB

Appendix E
Ground penetrating radar measurements at drill site 5
Johan Nissen
Malå Geoscience AB

Appendix F
Boreholes HFM14 and HFM15 at drill site 5 – drilling, logging and interpretation
Lars-Åke Claesson, Mirab Mineral Resurser AB
Göran Nilsson, GNC AB

Appendix G
The phenomenon of "soil-filled fractures" in crystalline rock – origin and potential implication on a repository
Roland Pusch
Geodevelopment AB

As indicated earlier, these documents represent independent contributions by their respective authors, although background data and some results are shared, and there are some overlaps and cross-references.

The sections below summarize important investigation results, extracted from the appended documents. For details and references – see appendices.

4 Main results

4.1 Quaternary deposits

Overburden thickness at drill site 5 varies from almost zero to c 5 m. In contrast to the rugged surface morphology of the underlying rock, the overburden surface was rather flat and almost horizontal. Investigations of the northeastern wall cut revealed an overburden comprising two major lithological units of till (Figure 4-1). The lower is described as a deformation till, formed by sedimentation of debris flow as well as sorted material and subsequently deformed by moving ice. The upper unit is interpreted as a basal till, likely deposited by an ice movement direction from north. It is likely that both units were deposited during the same glaciation. Pollen analyses of samples from the sediments suggest an original pollen deposition under interglacial conditions, but do also indicate that the microfossils are not in situ. Neither the composition and structure of the sediments, nor the contained pollen flora show any notable differences from what may be described as typical conditions in the Forsmark area.

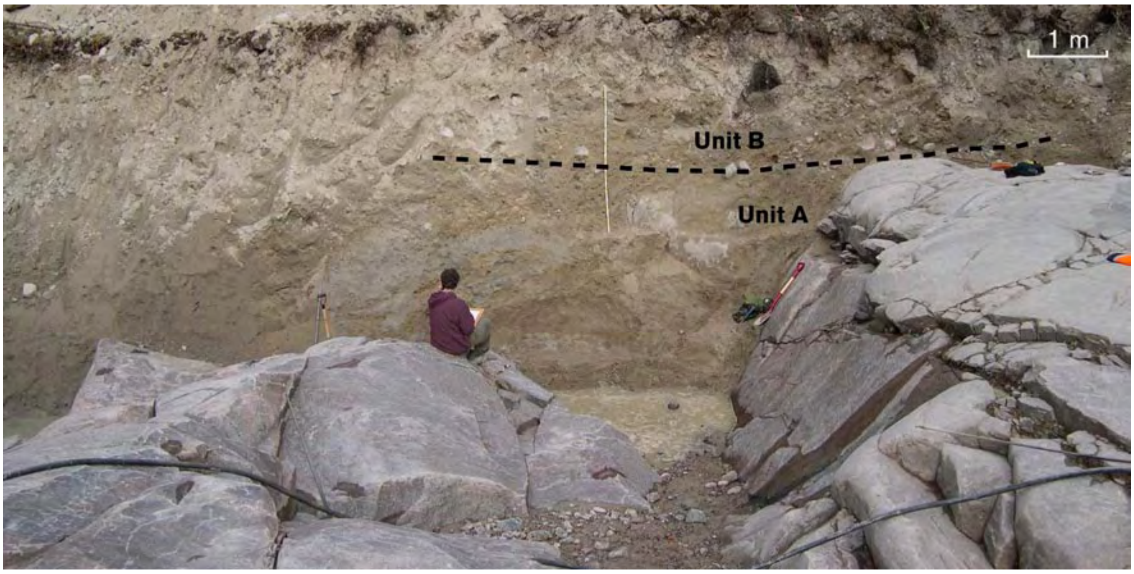

Figure 4-1. *Drill site 5, with the overburden as seen in the northeastern wall of the excavation in the background. Unit A denotes the lower deformation till and Unit B the upper basal till.*

4.2 Bedrock surface

4.2.1 Geometry and rock types

Figure 4-2 shows a 3D representation of the excavation, based on detailed surveying. Excavation was done in two steps. First the more or less rectangular part towards NE was stripped. Then, when the fracture pattern was to be seen, the extension towards SW was added in an attempt to trace NE-SW striking fractures over a longer distance. The excavated area was about 500 m^2. The rock surface dips to towards NW, but in a stepwise and irregular fashion.

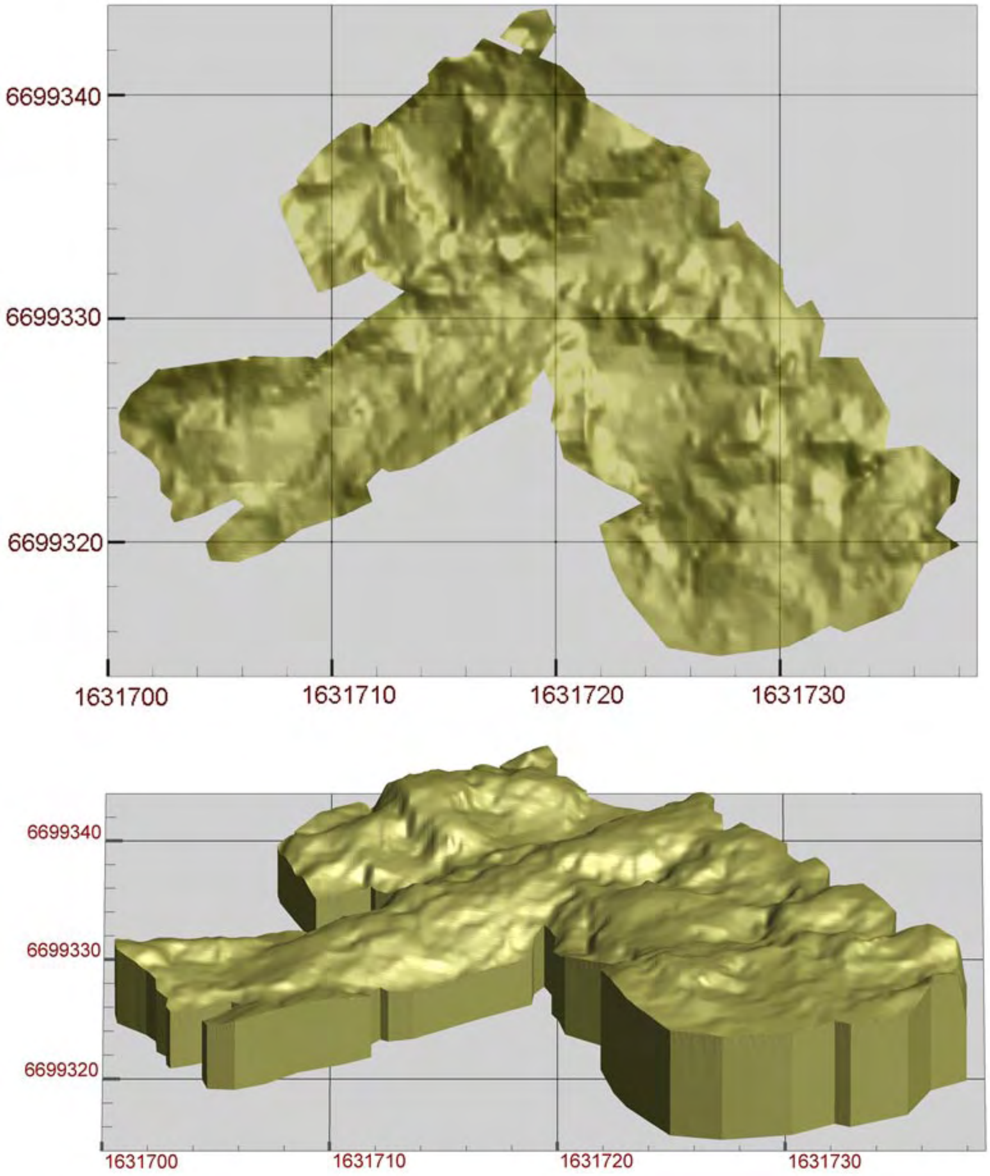

Figure 4-2. *Geometry of the excavation at drill site 5, as obtained from detailed surveying. Upper: Plan view. Lower: Perspective from south.*

The dominating rock types are fine-grained to medium-grained granites with a few amphibolite dykes. Glacial striae is abundant over the outcrop, and three different sets were observed. The dominating set is oriented approximately 360°–180° indicating an ice flow direction from N. The other sets indicate ice flow directions from NW and NNE respectively. It is likely that the evidences of ice movement from N at drill site 5 exemplify the ice movement direction that has been interpreted as the youngest in the Forsmark area.

4.2.2 Fracturing

For the most part, the bedrock surface is rather fractured. Table 4-1 summarizes data from detailed fracture mapping, yielding a total of 1280 fractures.

Corresponding data, although only for fractures with trace lengths larger than 50 cm, were at the time available from a number of other sites at Forsmark (drill sites 2, 3, 4 and Klubbudden). Table 4-2 shows a comparison with respect to relative fracture frequency (fractures per unit area) and portion of fractures classified as open. It is seen that the fracture frequency at drill site 5 is similar to that of the other sites, but a much larger portion of the fractures are open. Note that open fractures could be either sediment-filled or not.

Fractures shorter than 50 cm were only mapped along a few scan lines at the other sites, so no comparisons can be made. The general impression, however, was that short fractures were much more common at drill site 5 than at any of the other sites. As can be seen in Table 4-1, fractures of this category mapped at drill site 5 were without exception classified as open.

Table 4-1. Results from detailed fracture mapping at drill site 5.

Fracture trace length	Open fractures	Closed fractures	All fractures
Trace length < 50 cm	367	0	367
Trace length > 50 cm	560	353	913
Total	927	353	1280

Table 4-2. Fracture mapping data from drill site 5 compared to corresponding data from other sites (fractures with trace length > 50 cm).

	Drill site 5 (site average)	Other sites at Forsmark (range for site averages)
Relative fracture frequency (fractures per m^2)	1.8	1.6–3.7
Percentage open fractures	60	1–6

Indications of glacial impact

Special attention was paid to signs of glacial impact on the state of fracturing and attempts were made to distinguish fractures featuring such impact from apparently older fractures. Conducting such a classification is a matter of expert judgement, since no strict methods or criteria are available. The experts involved, however, devoted significant efforts to assess fracture age and history on the basis of careful field examination. Openness and glacial abrasion were taken as main criteria. The work was also supported by microscopic studies of a number of samples taken from selected fractures.

Table 4-3 summarizes the results of this assessment. The term "glacial" fractures refers to both fractures that were judged to have their origin in late- or postglacial age, and older fractures displaying clear indications of reactivation/reopening due to glacial impact. The term "old" thus denotes fractures free from signs of glacial impact. Figure 4-3 shows the same data projected on a plan view of the outcrop. The shallow, southeastern part of the excavation was excluded from classification since there were clear evidences of weathering as well as root and frost bursting of the rock surface.

It should be noted that the numbers given in Table 4-3 are estimates based on to some extent subjective judgement. Still, the conclusion remains that a significant portion of the fractures bear evidences of glacial impact. Both field examination and microscopic studies show that some of the glacially impacted fractures are of older origin, and have been reactivated.

Table 4-3. Classification with respect to age and openness of fractures mapped at drill site 5. Definitions of "glacial" versus "old" fractures are given in the text.

	Open fractures	Closed fractures	All fractures
"Glacial" fractures	707	0	707
"Old" fractures	17	222	239
Unspecified fractures	203	131	334
Total	927	353	1280

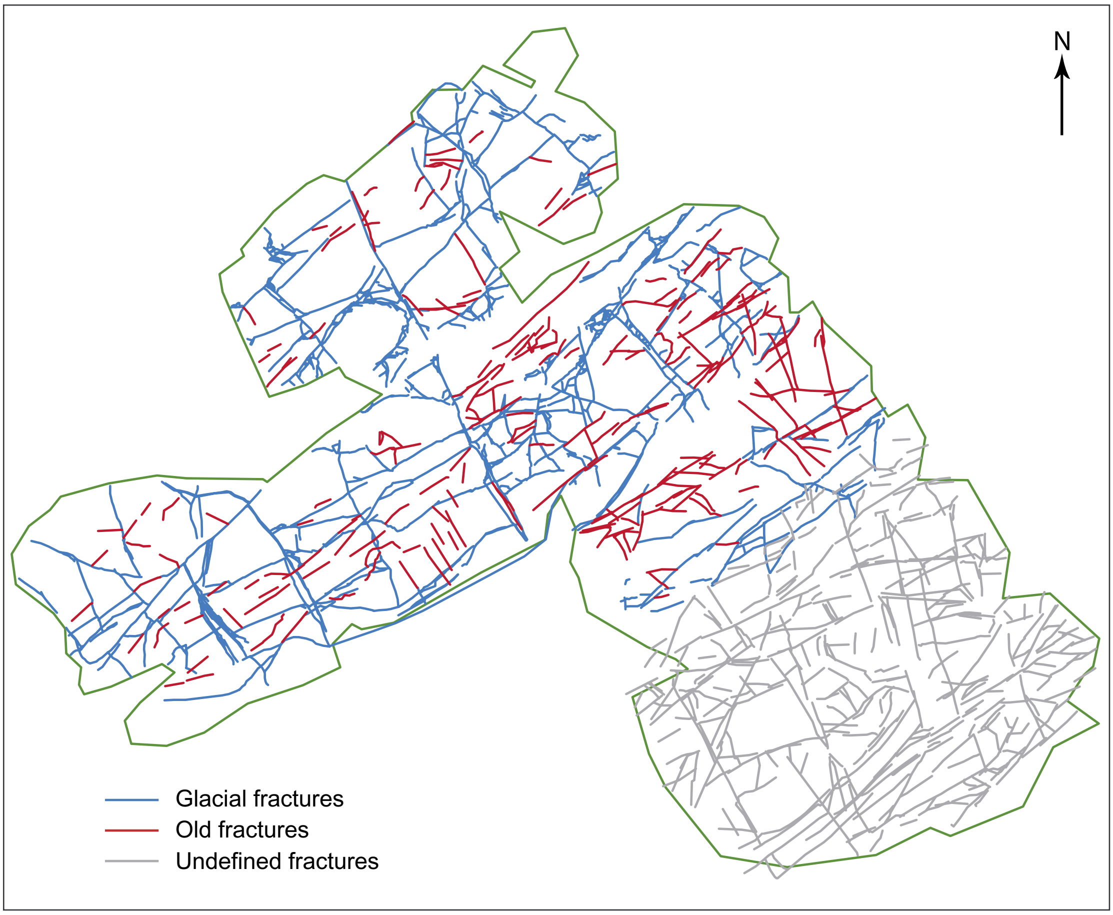

***Figure 4-3**. Fracture data from Table 4-3 displayed on a map of the exposed rock surface at drill site 5.*

Evidences for this include crystallized quartz on many fracture surfaces. However, fractures with fresh, unweathered surfaces without coating or staining (or occasionally with calcite from possibly recent precipitation) are also to be found, although expert views on the abundance of such fractures appear to be somewhat inconsistent.

Orientations

Most of the fractures mapped at drill site 5 can be assigned to three sets, two of which are steep and one subhorizontal. This is in line with data from the entire investigation area at Forsmark, but drill site 5 deviates from the other mapped sites in that orientations show a larger scatter. Thus, fracture sets are less distinct and there are also randomly striking, preferably steep fractures. Closer examination reveals that fractures classified as old are more distinctly concentrated to the three sets than those classified as glacial. Another observation is that many of the randomly striking fractures are short, glacial fractures often interconnecting larger, more dominating features.

Characteristics

The most spectacular features seen at drill site 5 are the extensive fractures striking mainly NE-SW and dipping gently to the SE. Figure 4-4 shows two of the predominant examples. According to the nomenclature adopted they should be termed glacial since they were filled with up to 20 cm of glacial sediments. Their origin however is judged to be older. The impression was that the superficial rock blocks overlaying these major fractures had been uplifted and in some cases slightly rotated relative to the underlying bedrock.

The glacial sediment infillings found in these fractures were investigated in the field and samples were taken for pollen analysis. The outer parts of these fillings consisted of unsorted sediments and crushed rock with maximum grain sizes approaching the fracture aperture. Further into the fractures, sediments were more fine-grained and consisted largely of laminated silt and fine sand, see Figure 1-4. The material composition and structure suggest inflow of sediment-bearing water into the fractures, followed by quiet sedimentation. No signs were found of outwards and/or turbulent flow or material transport from the fractures. Pollen analyses of samples of fracture infillings showed a signature similar to that of the overlying till.

The fracturing observed in the superficial rock overlaying the major, gently dipping fractures showed a large variability in appearance. As verified by the mapping data, most of them were steeply dipping and open. A majority exhibited apertures less than 1 mm, but apertures in the cm-scale were also common. In many cases, apertures of near-vertical fractures were clearly related to the degree of freedom for lateral displacements of the blocks delimited by these fractures.

Frequent examples of fracture displacements leaving apparently fresh block edges with little or no signs of glacial abrasion were readily seen at the site. Examples can be seen in Figures 1-3, 2-2 and 2-3. Many of the displaced fractures were clearly older features that had been reactivated but fractures cutting through virtually intact rock were also to be seen. Examples were also observed where reactivation of older fractures seemed to have generated secondary fracturing of intact rock. The overall effect of the fracturing and block dislocations was a general expansion and partial disintegration of the rock overlying the major, sediment-filled fractures described.

__Figure 4-4__. Two of the predominant, gently dipping fractures containing sediments, both viewed from northwest. The lower photo also illustrates the uplift of the superficial rock overlying these fractures.

4.3 Superficial bedrock

The near-surface bedrock was investigated by means of a ground penetrating radar (GPR) survey over part of the excavation. GPR is one of few methods available that combines aerial coverage with potential to identify discontinuities below surface. Depth penetration is highly dependent on local conditions, but typically ranges in the metre-scale, up to c 10 m.

In the present case, the objective was primarily to provide information on the extension towards depth of some of the major, sediment-filled fractures documented at surface and judged to dip gently to the southeast. Figure 4-5 shows an illustrative example of the results obtained. The GPR-data revealed three main reflectors that could clearly be correlated with three predominant fractures documented at surface. The integrated interpretation of all GPR profiles basically yielded similar results, i.e. reflectors dipping gently to the southeast that could be attributed to major fractures at the surface.

The maximum depths to which the structures in Figure 4-5 can be interpreted from the GPR-data are c 2 m, 3 m and 8 m respectively. It is not clear whether this reflects an actual termination (or closure) of the fractures, or merely the depth penetration of the investigation method. Drilling was required to through more light on this important question.

4.4 Conditions towards depth

4.4.1 Boreholes

Surface documentation and GPR-surveying showed that the anomalous fracturing at drill site 5 involved the uppermost few metres of bedrock. A key question then was whether they persisted to larger depths. This question called for borehole investigations and altogether three percussion boreholes were drilled at the site. Figure 4-6 shows borehole positions in relation to the site geometry. The two holes termed HFM14 and HFM15, reaching vertical depths of c 130 m and c 70 m respectively, were drilled diagonally below the site from a location on the southern side the excavation. The complementary vertical hole HFM14B, only 4 m in depth, was drilled from a nearby location.

During drilling, parameters such as penetration rate, drill cutting composition and water flow rate were monitored. After drilling, a comprehensive program of borehole investigations was executed. This included TV-camera (BIPS), borehole radar (RAMAC), conventional multi-method geophysical logging, pumping tests and in one of the holes also flow logging. Test results formed the basis for interpretation in terms of rock types, state of fracturing and hydraulic conditions.

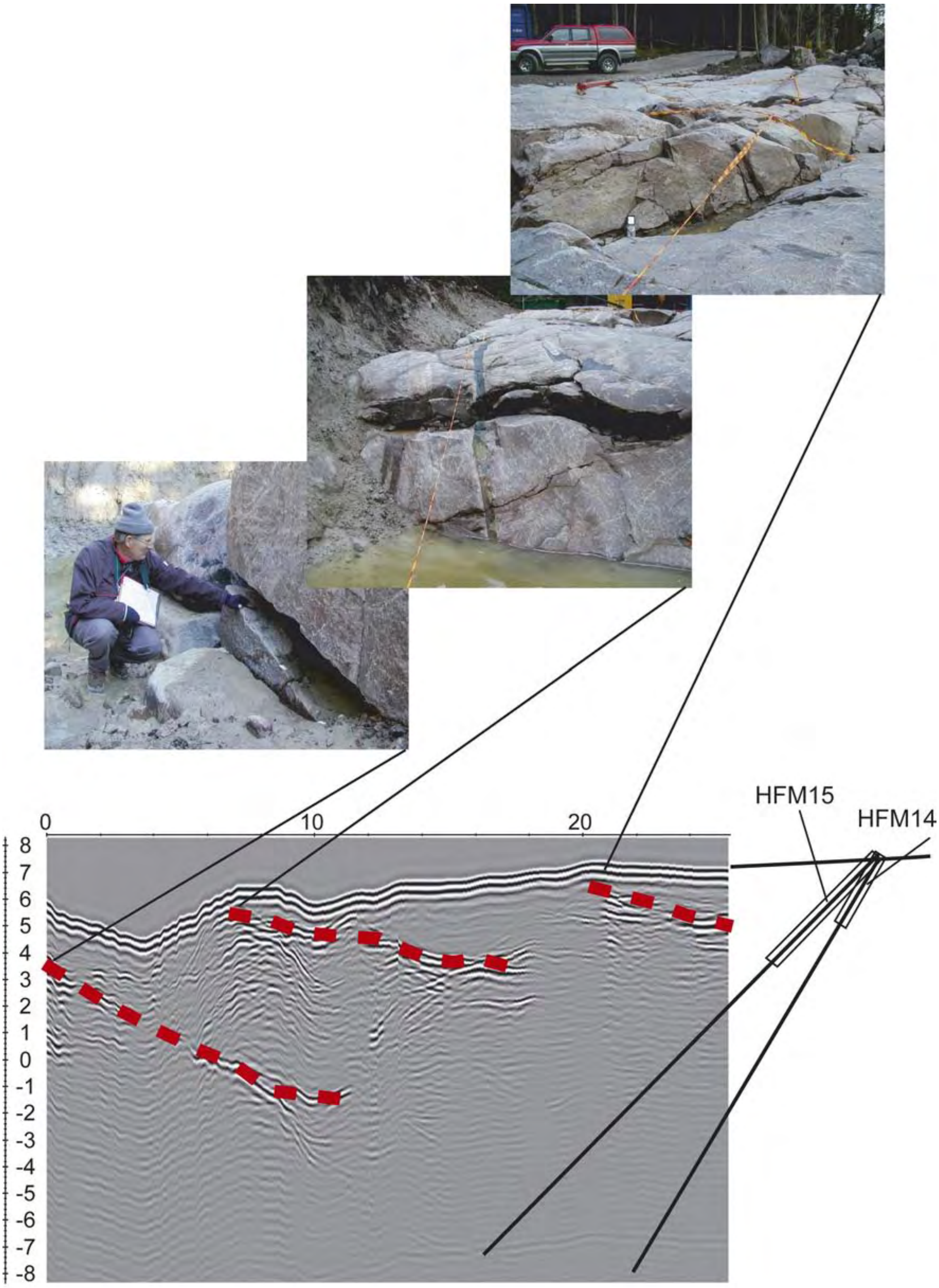

Figure 4-5. *Three major fractures at drill site 5, as documented at surface and interpreted from GPR measurements along a NW-SE section.*

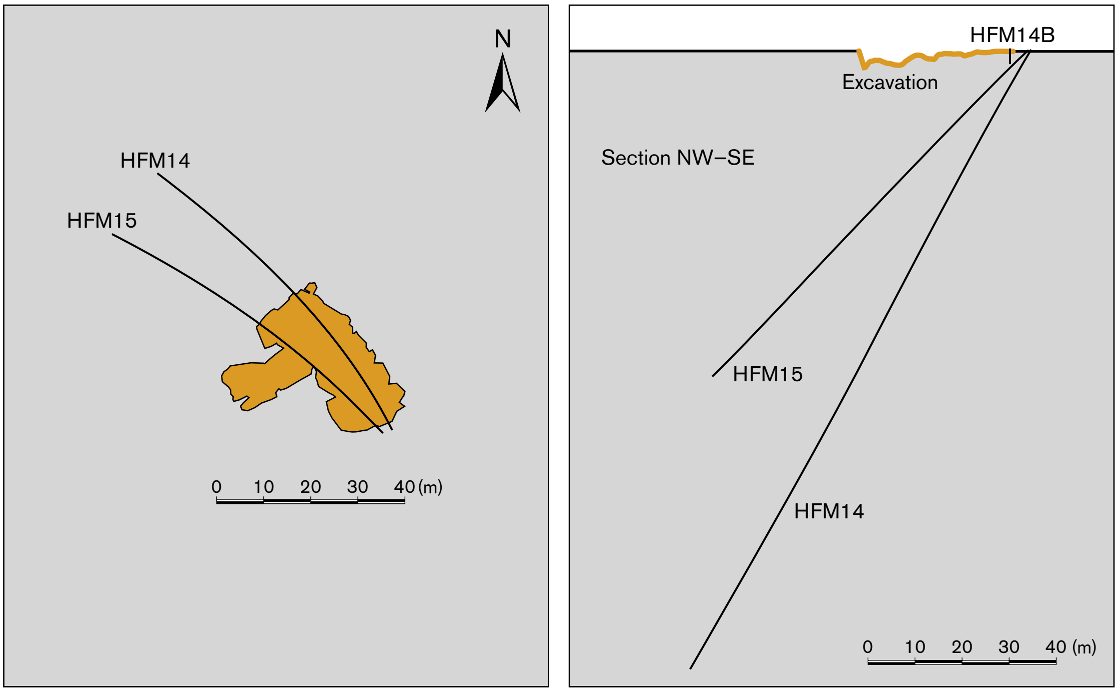

Figure 4-6. *Percussion boreholes in relation to the geometry of the excavation at drill site 5.*

4.4.2 Rock conditions

Important results from the borehole investigations are summarized in Figures 4-7 and 4-8. Figure 4-7 shows a vertical, NW-SE section of the uppermost 20 m at drill site 5. The boreholes are projected on the section (neglecting deviation and the small differences between the orientation of the section and the borehole bearings). Starting from surface, the most striking observation is the wide, open fracture or fracture zone intersected at some 3 m depth. In all three holes, observations during drilling indicated an approximately 0.5 m long section with crushed rock and/or soil material. Much of the soil material was flushed away during drilling, leaving large open fractures or voids. The three major, gently dipping structures inferred from the ground penetrating radar survey, here denoted GPR1, GPR2 and GPR3, are also indicated in the figure. The large fracture observed in the boreholes is to all probability identical to GPR1. Thus, this structure appears to extend more or less horizontally to the southeast, at least to a distance corresponding to the borehole intersections. It is also evident that the large aperture (decimetres) and soil filling persists to a depth of at least 3 m.

For the remainder of the depth interval shown in Figure 4-7, i.e. below the large fracture at c 3 m and down to 20 m, data show low fracture frequencies. Orientations are not indicated in the figure, but examination of data shows that a majority of the fractures are subhorizontal, although steeply dipping sets are also present. More importantly, there are no indications of unusually large fracture apertures or presence of soil material in any of the fractures. GPR-records allowed the fractures GPR2 and GPR3 to be traced from surface and some 10 m into the bedrock. Extrapolating positions and orientations from the GPR-results yields that these two fractures would intersect HFM14 and HFM15 at c 6 m and c 15 m vertical depth respectively. Whether some of the open fractures observed at these depths in the holes do in fact represent the continuation of GPR2 and GPR3 can not be determined. (A 10 cm wide, crushed zone observed at about 7 m in HFM15 is a possible candidate.) What can be stated, however, is that neither fracture apertures comparable to those seen at surface,

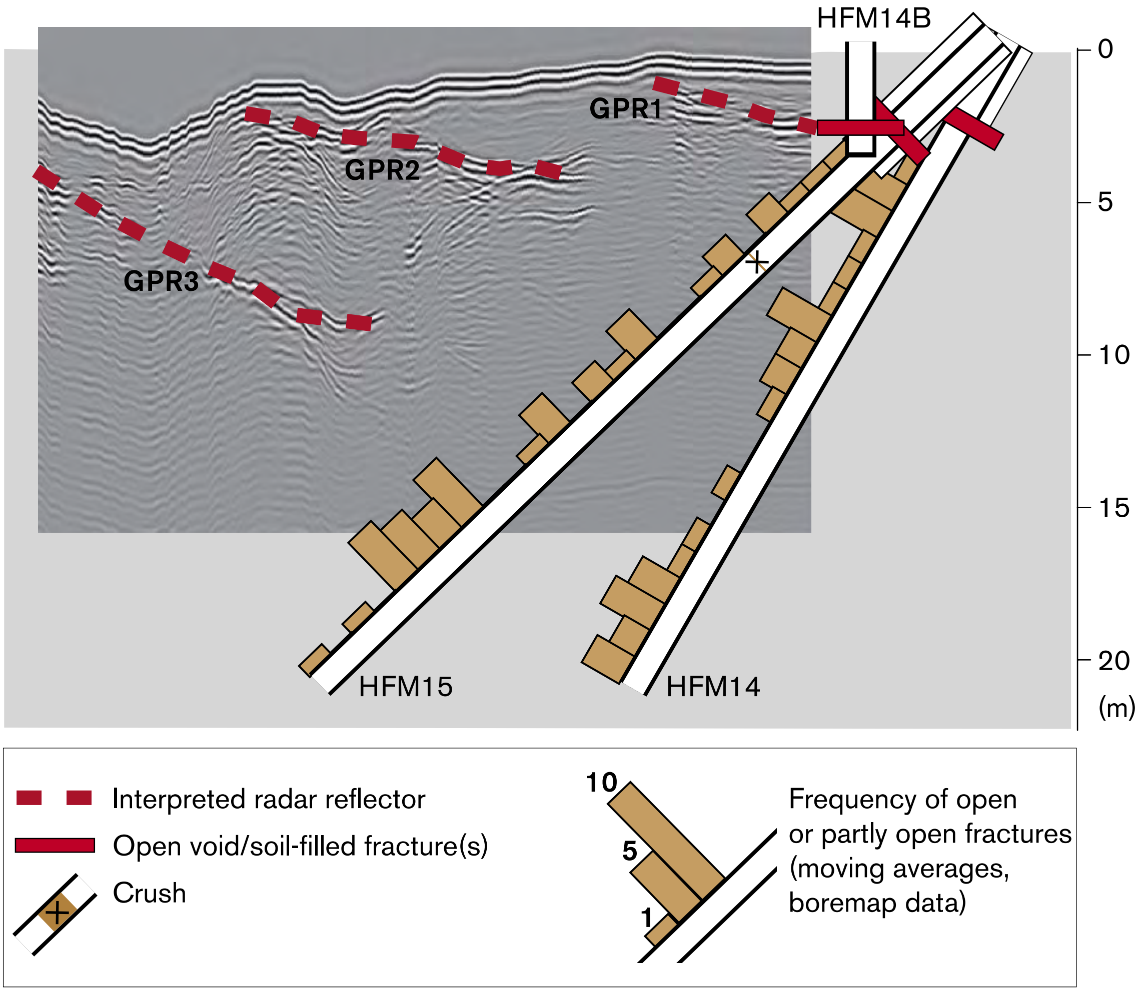

Figure 4-7. *NW-SE section of the uppermost 20 m at drill site 5, showing main results from the borehole investigations, together with main fractures inferred from GPR-surveying.*

nor any sign of soil infillings, can be found in the boreholes at these depths. It is therefore concluded that the uplifting- and sediment filling processes are, at least in these two cases, phenomena that involves only the superficial rock mass.

Figure 4-8 shows the same section as Figure 4-7, but in a scale such that the boreholes are displayed to their full lengths (neglecting borehole deviations). As far as fracturing is concerned, data towards depth offer few surprises. Overall fracture frequencies are low. In both HFM14 and HFM15, increased fracturing indicates a possible fracture zone within the approximate depth interval 60–67 m. In HFM14, another similar zone is indicated at 79–90 m. The fractures constituting the inferred zones are largely subhorizontal. The lithological conditions (not indicated in the figures) along the boreholes are comparable to those at surface and do not show any significant changes with depth.

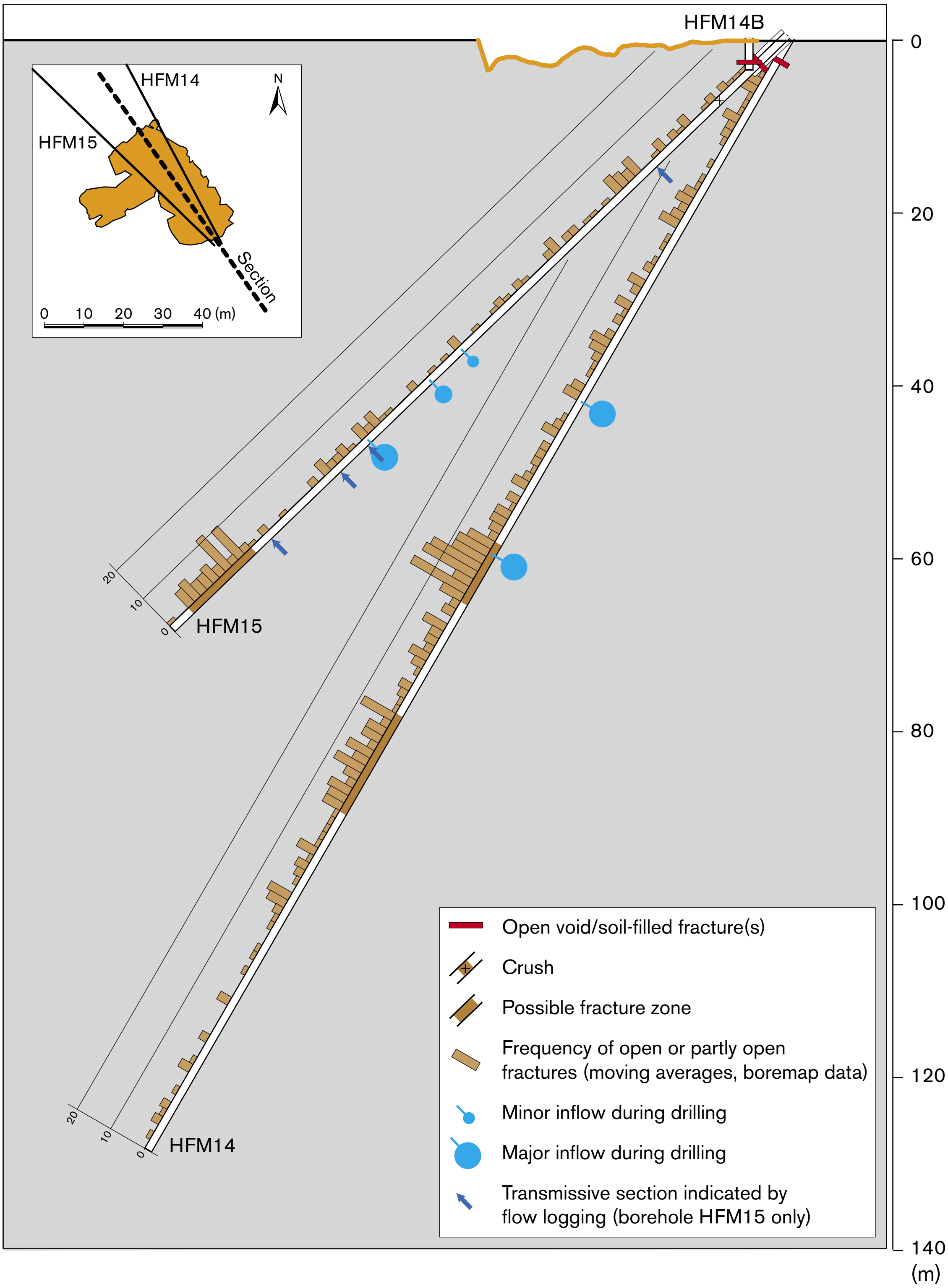

Figure 4-8. *NW-SE section of the uppermost 130 m at drill site 5, showing main results from the borehole investigations.*

4.4.3 Hydraulic conditions

Figure 4-8 also indicates hydraulic conditions observed in the boreholes. The first indication of a conductive structure (excluding the open, superficial fractures resulting in surface discharge of drilling water) is observed at about 16.5 m in HFM15. A number of water bearing structures are found within the approximate interval 40–60 m. Some of these structures are highly conductive. Water inflows to the boreholes tend to occur at distinct positions and can in many cases be correlated with individual fractures. Another observation was that hydraulic connections exist between the holes at drill site 5, and holes several hundreds metres away.

Altogether, the hydraulic conditions observed in the boreholes at drill site 5 are in accordance with the general trends that the site investigation work so far has revealed, for the depth interval in question and within the tectonic lens at Forsmark.

5 Comments and conclusions

As outlined in Section 1.2, the observations made when uncovering the rock surface at drill site 5 prompted the following questions:

- How can the conditions at drill site 5 be described, quantitatively and in more detail?
- Are the anomalies confined to the superficial rock, or do they reflect disturbances at larger depths?
- What can be learnt from other studies of similar phenomena?
- What events and mechanisms may have caused the present conditions?
- Are there potential implications on site suitability?

Below, these questions are addressed in the light of the reported investigation results.

5.1 How can the conditions at drill site 5 be described, quantitatively and in more detail?

It is considered that the investigations conducted provide a relevant and satisfactorily detailed documentation of the site. This applies both when considering the work specifically in terms of input to the site investigation, and in terms of contributing a case study to the geoscientific community at large. This was also the conclusion from the seminar held on October 29, 2003, where interim results were presented.

Established, quantitative methods have been employed to the extent possible. Inevitably however, parts of work have relied upon description and expert judgement, since there are no strictly objective methods or classification systems to be used. This applies in particular for the characterization and classification of fractures with respect to their origin and indications of glacial impact.

5.2 Are the anomalies confined to the superficial rock, or do they reflect disturbances at larger depth?

The surface investigations provide a thorough characterization of the superficial rock mass, down to at most a few metres, but there is no basis for “blind” extrapolation towards larger depth. Thus, one has to rely upon other investigation methods, in the present case ground penetration radar surveying (GPR) and percussion drilling.

The GPR records allow a number of the dominating, gently dipping fractures seen at surface to be traced to a few metres depth, in one case about 8 m. Whether the trace depths reflect the maximum penetration depth of the method or an actual change of fracture characteristics (fracture closure) can not be determined with certainty.

The drilling verifies the presence of a very large, open and soil-filled fracture (or fracture zone) at roughly 3–4 m depth. Below this depth and down to at most 10 m, fractures occur that can possibly be correlated to fractures that – as they appear at surface – are open and sediment-filled. The fractures encountered in the boreholes, however, show no signs of either unusually large apertures or soil infillings. Thus, no obvious signs of abnormal conditions can be observed below about 4 m in any of the boreholes. Further assessment must be based on comparisons with results from elsewhere. The relevant reference is the generalized picture of the uppermost c 100 m of the bedrock, within the tectonic lens at Forsmark, as it has emerged from investigations conducted so far. Viewing the borehole data from drill site 5 against this background, it is difficult to see anything that would indicate deviating conditions (excluding again the uppermost c 4 m). This applies to lithology and fracturing (rock type, fracture frequency-, orientation- and characteristics) as well as hydraulic conditions (occurrences of conductive fractures, water conductivity).

Thus, in summary the investigation results from drill site 5 support the following conclusions:

- The disturbances observed are surface-related phenomena confined to the superficial rock.
- A conservative estimate of the depth to which these phenomena have observable effects on the state of fracturing would be 10 m; a more probable estimate would be 5 m.

5.3 What can be learnt from previous studies of similar phenomena?

5.3.1 Investigations at the Forsmark nuclear power facilities

Scope, main results and conclusions

The construction of the nuclear power plants at Forsmark in the 1970's required extensive rock excavation work, both from surface and in tunnels. Excavations created reached maximum depths of about 75 m. Surface- and borehole investigations were conducted to support the construction work, but also for more research-oriented purposes. During this work, flat-lying fractures with infillings of unconsolidated sediments were often encountered in the shallow bedrock.

During the construction period, the superficial rock mass was investigated in detail by Anders Carlsson who presented comprehensive field data, interpretations and conclusions in the form of a doctoral thesis /Carlsson 1979/. Emphasis was on the state of fracturing, as observed on exposed rock surfaces including walls of large excavations. Dimensions of the exposed surfaces were tens of metes in height and several hundred metres in length. Figure 5-1 shows two photographs of one of these walls, providing an excellent overview of the state of fracturing.

Carlsson distinguished a number of fracture sets, one of which was formed by extensive, horizontal and subhorizontal fractures which were abundant in the shallow bedrock. He also found that these fractures deviated from others in a number of respects. Firstly, they showed a marked depth dependency, such that both frequency and extension decreased with depth. Typical fracture spacings towards surface were 0–2 m. Fracture lengths varied widely; tens of metres were often recorded and the maximum value was 170 m. Secondly, apertures were larger than for other fracture sets. Apertures in the centimetre-scale were common, and there were examples of several decimetres. Apertures generally decreased with depth. Thirdly, a large portion of the horizontal and subhorizontal fractures at depths down to about 5 m were filled with sediments. Below this depth, sediment infillings were uncommon. The deepest occurrence was documented at 13 m.

Figure 5-1. *A shaft wall of a storage basin for industrial water under construction at Forsmark. This was one of several excavations investigated by /Carlsson 1979/ during the period when the nuclear power plants and auxiliary facilities were constructed. The system of extensive, horizontal and subhorizontal fractures can be seen, as well as steeply dipping fractures. The outstanding, horizontal fracture is c 0.5 m wide and filled with sediment. Photo Göran Hansson/N.*

The fracture filling material was investigated with respect to composition, structure, mechanical characteristics and pollen flora. Grain size distribution was found to fall predominantly within the silt fraction, with clay and/or sand in minor proportions. Rock fragments embedded in the material occurred occasionally. Lamination indicating transport by streaming water and sedimentation was commonly seen in the filling material. The temporal history of the deposition of the material could not be unambiguously determined. Preconsolidation pressures calculated from laboratory tests as well as investigations of pollen flora indicated deposition prior to the last glaciation. On the other hand, the absence of displacements post-dating deposition of surface rock slabs overlying filled fractures, and the largely undisturbed character of the sedimented filling material, strongly suggested deposition in connection with the latest deglaciation.

Carlsson concluded that the horizontal and subhorizontal fractures were basically results of so called sheeting, a surface-related mode of fracturing commonly seen in brittle, competent rock. The fundamental mechanism behind sheet fracturing is vertical extension due to vertical unloading and/or horizontal loading. Given the site specific data presented, combined with other knowledge of this type of fracturing, Carlsson's conclusion can hardly be questioned. Mineral coatings on some fracture surfaces indicated that initial stages of fracturing occurred long before recent glaciations. There was however also clear evidences that the further development of the sheet structures post-dated other structural features in the superficial rock mass.

Based on his comprehensive data, Carlsson also examined various hypotheses for explaining the extreme fracture apertures and deposition of soil infillings. One theory which had been proposed at the time was repeated freezing and thawing of the near-surface rock (freezing causing at least partly irreversible expansion of sedimented material, allowing more material to be transported into the fractures during periods of thawing). However, Carlsson found this theory inconsistent with some of his data and with the fact that marine conditions prevailed during the latest glaciation cycle. He concluded that the most plausible explanation for the conditions observed was the sequence of rock stress alterations occurring during a deglaciation: The reduction of ice load and recession of the ice margin will generate a complicated pattern of large and rapid stress changes in the shallow bedrock. The end result is a relief of vertical stress (as compared to conditions during glaciation), while horizontal stresses may remain more or less unchanged or encounter a to some extent time delayed reduction. These conditions can trigger new sheet fracturing phenomena or further development of pre-existing sheet structures. The process of fracture widening can be explained by wedging effects from rock fragments breaking loose from the fracture surfaces, prohibiting fracture closure. Then, the filling material can be hydraulically transported into the widened fracture and sedimented, given a suitable hydraulic gradient only.

In summary then, the conclusion was that the state of fracturing in the near-surface bedrock at Forsmark can be attributed to fundamentally well understood processes, though operating in an unusually large scale and with some uncommon consequences.

Resemblance with drill site 5

The investigations by Carlsson covered large rock exposures, including both natural rock surfaces and vertical cuts at Forsmark. In contrast, documentation at drill site 5 was limited to a rather narrow "window" of exposed rock, and subsurface information was essentially confined to borehole data. Carlsson's study therefore contributes very valuable background knowledge for the interpretation of observations at drill site 5.

It is clear that drill site 5 fits well into the characteristics of the shallow bedrock at Forsmark, as presented by Carlsson. Striking similarities can be seen as regards general fracture pattern, depths to which anomalous fracture apertures and sediment infillings are found, characteristics of filling material and the apparent absence of block displacements post-dating the deposition of filling material. Carlsson verified that the major, sediment-filled fractures were actually sheet structures. This is likely to be the case also for the major, gently dipping fractures observed at drill site 5, but this can not be concluded with certainty. As discussed in a subsequent section, the alternative interpretation is that they are local manifestations of structures on a larger scale.

5.3.2 Other studies

Fracturing

Disruptions of the bedrock surface of proven or possible late- or postglacial age are phenomena that have drawn considerable attention in recent years. Examples presented range from displacements of minor surface blocks and so-called boulder caves, to large-scale fault movements. Theories on the geomechanical background of these various forms of field occurrences have been presented and discussed. Boulder caves and their possible origin are of some interest in the present context. Well known cases are *Bodagrottorna, Trollberget* and *Gillberga gryt*, the last one not far from Forsmark. There are different opinions as to the origin of these features. Mörner and his co-workers have repeatedly claimed that they are results of post-glacial seismotectonic activity involving major earthquakes /Mörner 2003/, while most other investigators consider various forms of glacial impact as a more credible explanation. /Lagerbäck et al. 2005/ have recently discussed this matter, from the perspective of possible relevance for conditions in the Forsmark area. They argue that the mentioned boulder caves were likely formed by intense rupturing of irregularities in the bedrock surface, under an overriding ice sheet. A striking abundance of angular boulders in the vicinity of the actual boulder cave formations, primarily along the major ice flow direction, is adduced as a strong argument for this explanation. They also consider that the disturbances seen at drill site 5 are results of similar glacial processes, but of lesser intensity and degree of development than those creating boulder caves.

Sediment filling

Besides the work by Carlsson referred above and the observations at drill site 5, the drilling operations at a number of other sites within the area currently under investigation at Forsmark have added further indications of sediment filling in fractures. In several cases sections ranging from centimetres to decimetres in width, and containing very soft material, have been penetrated during percussion drilling. Loose material from these sections is often suspended in the drilling water and transported to surface. Observations clearly indicate that the material is soil-like, typically silty, and forms filling in generally subhorizontal fractures. Such soil-fillings have been encountered down to at least c 50 m depth, i.e. much deeper than the similar features at drill site 5. An interesting observation is that all occurrences at depth seem to be correlated with more or less well identified fracture zones, in most cases some member of a set of subhorizontal fracture zones striking roughly NNE and dipping on average 25° to the SE.

Apart from Forsmark, observations of soil fillings have recently been documented at Björklinge near Uppsala /Lokrantz 2004/. Other observations in connection with excavation work have been reported from Umeå /Pusch 2003/, hydropower facilities in northern Sweden and a number of places in the Stockholm region /Carlsson 1979/. A comment often heard from persons with long experience in rock engineering is that soil occurs occasionally in superficial fractures, but is not paid attention to unless some practical consequences can be seen. In summary, it appears that soil filling in superficial fractures is certainly not common, but perhaps not quite as exceptional as it may appear from a brief survey of the literature.

5.4 What events and mechanisms may have caused the present conditions?

The data from drill site 5 unambiguously support the conclusion that the disturbances of the superficial bedrock are of late- or postglacial age. They also provide some understanding of the modes of fracturing and block dislocation, while interpretations of the underlying causes and mechanisms remain more speculative.

Simplifying, a primary and a secondary mode of deformation may be distinguished. The primary mode is the widening of gently dipping fractures, with associated uplift and slight rotation of overlying slab-shaped blocks. This provides access for hydraulic transport and sedimentation of the filling material. The secondary mode of deformation is fracturing of the uplifted surface bedrock, including both reactivation of existing fractures and rupture of previously intact rock. This produces a multitude of fracture types, block displacements and partial disintegration of the surface bedrock.

Figure 5-2 illustrates two alternative conceptual explanations for the major, gently dipping fractures. The most likely alternative is that they are sheet structures. /Carlsson 1979/ proved this to be the case for the in all respects similar fractures he investigated some 2 km northwest of drill site 5. Another factor supporting this interpretation is the tendency of the fracture planes to curve towards surface. GPR- and borehole data indicate that orientations change as the fractures approach surface, from almost horizontal to a dip of about 25° at the surface intersections. The extensional fracturing mechanism causing sheet structures offers mechanical explanations for this geometry to develop, when initially horizontal fractures are extendend and eventually "find their way" to the surface. The sloping bedrock surface would facilitate such a process. The fact that anomalous fracture apertures and sediment fillings are found only in the uppermost few metres also support the concept of sheet structures.

The other possibility is that the fractures are local manifestations of the major, gently dipping fracture zone termed "A2" that has been identified during the site investigation work. According to current site models, the centre of this zone intersects ground surface some 250 m northwest of drill site 5. Its orientation agrees closely with the orientation of the major fractures at drill site 5 at their surface intersections. A number of smaller "sister zones", have been identified further to the southeast. As mentioned, material interpreted to be sediment infillings have been found in fractures within such zones, to depths of c 50 m.

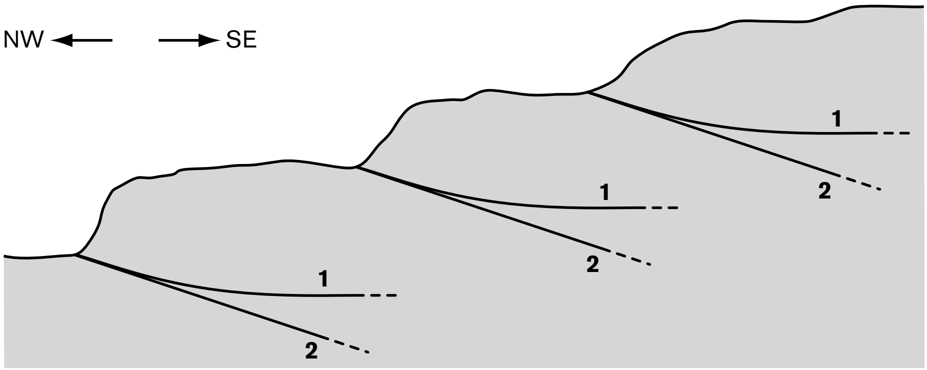

Figure 5-2. Alternative, conceptual explanations for the major fractures at drill site 5: 1) Sheet fractures, curving up towards their surface intersections. 2) Gently dipping fractures, attributable to the nearby, similarly oriented fracture zone A2.

The more puzzling question, however, is what course of events could possibly explain that the surface rock is displaced upwards, and remaining uplifted at least long enough for filling material to be intruded into the space below the uplifted volume. Appendix G to this report provides a brief overview of more or less conceivable theories, including stress-related mechanisms, large-scale liquefaction, and processes involving hydraulic jacking at an ice margin. /Carlsson 1979/ concluded that the opening-up of the sheet structures he investigated at Forsmark was most likely caused by rock fragments formed during intense sheet fracturing, and trapped between fracture surfaces thus prohibiting fracture closure.

Without pursuing a full discussion of alternative explanations, it is concluded that the scenario suggested by Carlsson provides the most rational explanation also for the fracturing and uplift phenomena seen at drill site 5. The main argument is simply that results from the investigations of both bedrock and overburden at the site support (or at least do not contradict) such a course of events.

Further arguments can be found by studying mechanically analogous fracturing- and failure processes occurring when rock is subjected to similar loadings under more controlled conditions. Extensional fracturing, very similar to sheeting but in a much smaller scale, can for example be generated under laboratory conditions. Another and useful analogue is the type of brittle failure around overstressed underground openings commonly referred to as spalling. Prerequisites for these types of failures are:

- Competent and brittle rock.
- Highly anisotropic stresses.

The rock at drill site 5 (as within most of the site investigation area) would certainly fulfil the requirement of competent and brittle rock. The generally sparse fracturing (neglecting the sheet structures themselves) may imply that this applies also to rather large rock volumes. The requirement of highly anisotropic stresses more specifically means:

- Little or no stress (i.e. lack of confinement) in one direction. This is the case perpendicular to a free surface (ground surface in the case of sheet formation, tunnel periphery in the case of spalling).
- Stresses in the other direction (i.e. parallel to the ground surface or tunnel periphery respectively) high enough to initiate failure.

The variations of near-surface, horizontal stresses over a glaciation cycle are difficult to estimate. It is likely though, that horizontal stresses higher than those prevailing today have existed at least for some time after deglaciation.

Under certain conditions, extensional fracturing of brittle rock can occur very suddenly and evolve more or less dynamically. The prerequisite is that the initially intact rock volume can accumulate an amount of instantaneously recoverable strain energy, exceeding that required to “drive” the fracture propagation once rupture has initiated. Part of the excess strain energy released upon rupture will then convert to kinetic energy, causing additional fracturing and dynamic rock movement. Such “explosive” failures are well known from tunnelling in high stress environments, were they can pose serious threats to stability and safety. Typical effects are that slabs and fragments of rock are suddenly thrown out from the tunnel roof or wall. When occurring at horizontal surfaces such as tunnel floors (more seldom seen), the typical result is an upheaval of the surface due to the formation of rock sheets along horizontal fractures, distortion and cracking-up of these sheets and associated widening of fractures. Neglecting the differences in scale only, the similarities with the superficial fracturing seen at Forsmark are striking.

A scenario involving explosive failure can also help to explain the diverse fracturing subdividing the uplifted rock sheets into smaller, angular and often displaced blocks. Slabs created by spalling in tunnels are often broken into smaller, box-shaped fragments along fractures more or less perpendicular to the orientation of the primary extensional fractures. The analogue at drill site 5 would be preferably steep fractures scattered in all directions and irregular displacements of block, which is exactly what has been observed. Other, less dramatic, mechanisms may also have contributed: Once the large sheets of rock had been detached from the underlying bedrock they lost support, resting on perhaps only a few points. The weight of the sheets themselves may have created tensile bending forces, causing them to rupture.

5.5 Are there potential implications on site suitability?

The crucial aspect of this question is the potential for implications on present and future conditions at depths within the interval 400–700 m, i.e. the interval within which a deep repository is planned to be located. Given the interpretation that the reported disturbances at drill site 5 are 1) confined to uppermost 10 m or less of the bedrock; 2) consequences of events that are as such conditioned by the proximity to the ground surface, it is indeed difficult to envisage any significant implications on site conditions at repository depth.

Considering implications for site characterization, it is self evident that surface conditions contrasting to those at deeper levels will hamper the use of surface- and shallow-depth data for predicting conditions at depth. This applies in particular to fracture statistics and hydrogeological properties. The only reliable means to mitigate such data bias effects is drilling and borehole testing to relevant depths, a fact which is well recognized within the ongoing site investigation.

If persistent over larger areas, the type of fracturing encountered will significantly alter the mechanical and hydraulic characteristics of the near-surface bedrock in the large scale. Sheet structures will, for example, greatly enhance hydraulic conductivity if they are open, but may have the opposite effect if they are sediment-filled (both have been experienced at Forsmark). Assessing possible implications of such characteristics of the shallow bedrock in terms of long term performance of a deep repository requires extensive analysis. Such analysis work is in progress, but further discussion of this matter is beyond the scope of the present study.

Concerns with respect to repository construction can be more readily appreciated. Thus, the shallow bedrock characteristics must be carefully considered in the design and construction of the shafts and tunnel decline forming access routes to a deep repository. The passage of a large sheet structure during shaft sinking may, for example, result in uncontrolled water inflow, unless appropriate precautions such as removal of possible sediment fillings and sealing of the structure by pre-grouting are taken.

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Appendix A

Description and assessment of glacial fractures at drill site 5, Forsmark

Lars Mærsk Hansen, Isabelle Staub, Jon Vestgård, Ola Forssberg
Golder Associates AB

June 2004

Summary

At drill site 5 abundant open, post- or late glacial fractures, here jointly referred to as "glacial fractures" were observed when the bedrock surface was exposed. A detailed documentation of the state of fracturing at the outcrop was conducted, and the more than 1200 fractures observed were classified with respect to appearance and type of glacial impact. Attempts were made to determine whether glacial fractures were actually reactivations of preexisting fractures, or represented fracturing through previously intact rock. A comparison was also made with other sites at Forsmark.

It is concluded that the glacial fractures observed at drill site 5 generally belong to the same sets as older fractures, and they are therefore regarded as being mainly reactivations of older fractures. Glacial fractures shorter than 0.5 m in length, however, tend to appear as "new" fractures with no host rock staining or mineral coating. They are generally steep and strike randomly.

A comparison of mapped sites at Forsmark shows that the fracture sets are similar at all sites (including drill site 5), though with minor variations in orientations and frequencies. The striking feature at drill site 5, not to be seen at the other sites, is the abundance of open late- or post glacial fractures, many of which with sediment infillings.

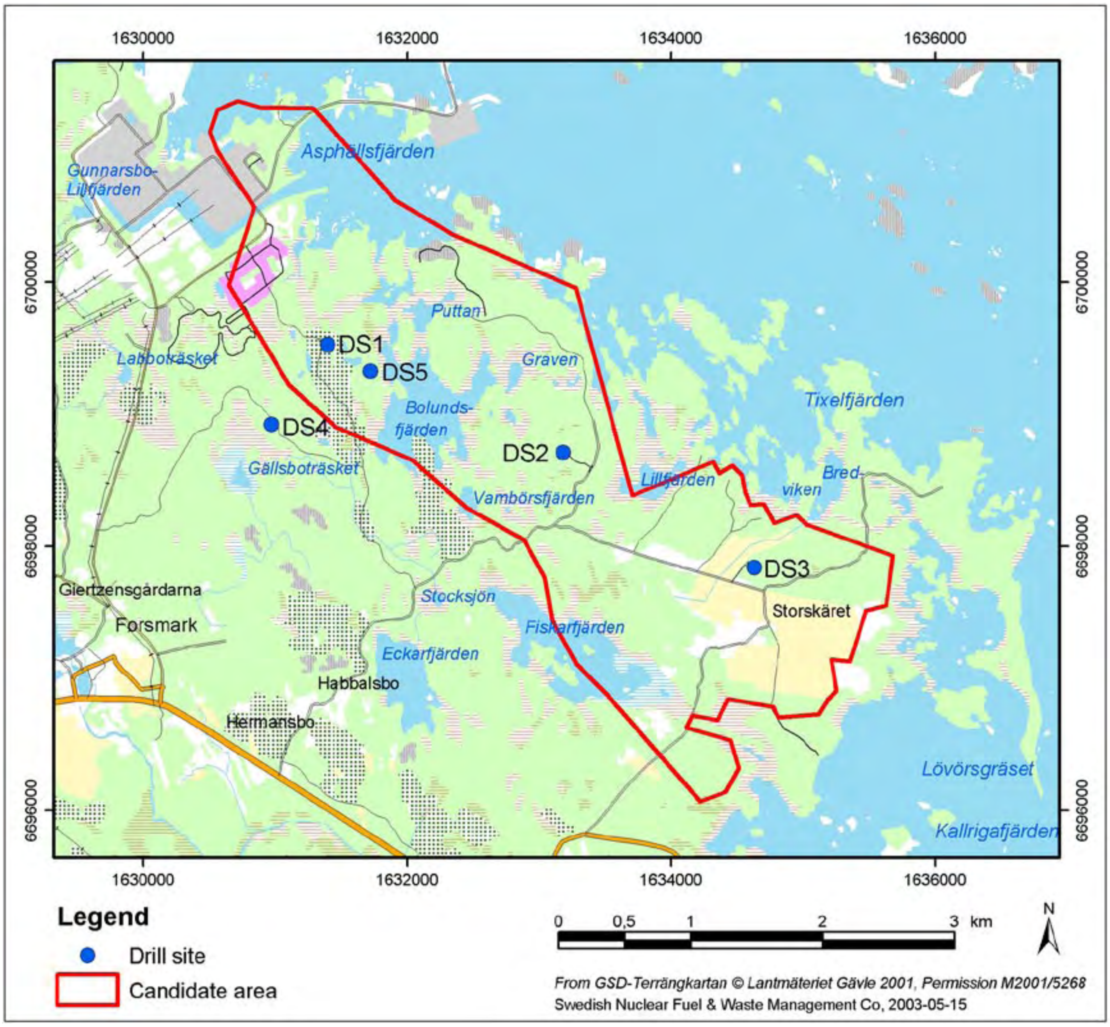
Contents

A1 Introduction

The investigation program at Forsmark includes detailed geological documentation of many of the drill sites selected for core drilling. Prior to establishing such a drill site, the soil cover is temporarily removed, the rock surface cleaned, and bedrock mapping is performed. Emphasis is on surveying and documenting fractures within the trace length interval 0.5–10 m. Upon completion of the mapping activities, the soil cover is restored.

This procedure was followed also at drill site 5, the area of which is ca 500 sq m. Initially, some 20 sq m were exposed rock, and some additional 150 sq m had a soil cover of less than 1 m. The remaining ca 330 sq m had a soil cover of 1 to 5 m. The methods employed for the bedrock mapping, the campaign and its results are presented in a report entitled "Detailed fracture mapping of excavated rock outcrop at drill site 5, AFM100201" published in the P-series of SKB reports (Hermanson et al. 2004). Figure A-1 shows the location of the site.

The complementary mapping work reported in this document was conducted in accordance with activity plan AP PF 400-03-96 and method description MD 132.003. No deviations from these controlling documents were encountered. Data have been delivered to SKB's database SICADA, where they are available by the activity plan number.



From GSD-Terrängkartan © Lantmäteriet Gävle 2001, Permission M2001/5268
Swedish Nuclear Fuel & Waste Management Co, 2003-05-15

Figure A-1. *Location of drill site 5 and other sites at Forsmark.*

Upon exposure of the rock surface at drill site 5, it soon became obvious that the fracture pattern displayed evidences of post- or late glacial activity (hereinafter referred to as "glacial fractures"). This included anomalous fracture apertures, uplift of surface blocks by up to 20 cm and infillings of sediments in some fractures. Figure A-2 shows the excavated rock surface viewed from the southwest. A graphic of the excavated rock surface with documented fracture pattern and locations of four more spectacular fracture concentrations, labeled Pl 1, Pl 2, Pl 3 and Pl 4 is shown in Figure A-3. Subhorizontal glacial fractures have been mapped beneath the large blocks in the far left of Figure A-2, and other glacial fractures are present in the far middle (cf Pl 2 and Pl 1 respectively, in Figure A-3).

Given this information, SKB initiated a series of field studies, to be carried out contemporaneously with mapping, in order to document these features in detail, investigate their extension at depth, and if possible determine the responsible processes and mechanisms. As part of this program, the following supplementary parameters were added to the mapping procedure for fractures:

- Indications of fracture origin and relative age.
- Indications of fracture reactivation.
- Survey of fracture displacements and related block movements.
- Comparisons with other drill sites at Forsmark.

The subsequent chapters summarize the fracture mapping data previously reported by /Hermanson et al. 2004/ and reports additional information gained from the supplementary study.

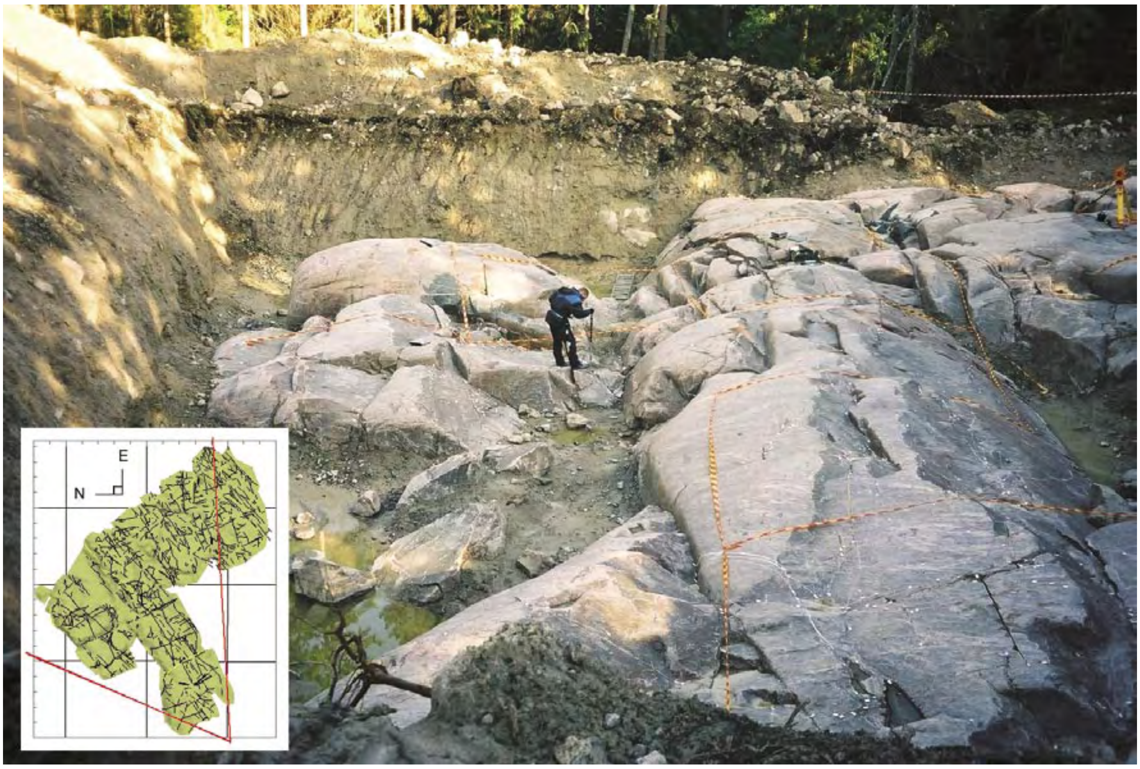


Figure A-2. *Detailed fracture survey at drill site 5 at Forsmark. View from the southwest. The red lines in the insert indicate approximate viewpoint and field of view.*

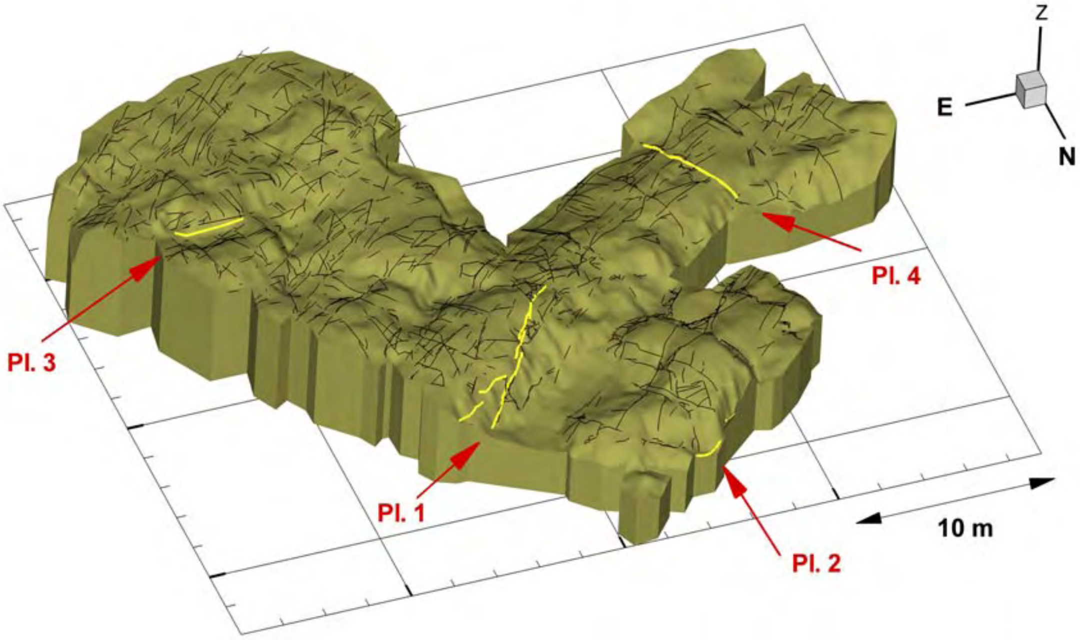


Figure A-3. *Block diagram of drill site 5 at Forsmark, with surveyed fracture pattern and dominating glacial fractures highlighted.*

A2 Fracture types and characteristics

In all, 1280 fractures were mapped at drill site 5, as shown in Table A-1. Fracture trace lengths between 50 cm and ca 10 m were recorded for 913 of the mapped fractures. Of these, 560 were open, and in addition 367 open fractures with trace lengths between 5 and 50 cm were mapped.

In a separate study conducted by a team from the Swedish Geological Survey (Robert Lagerbäck, Hanna Lokrantz and Joachim Albrecht), 707 of the in total 927 open fractures were judged to be of post- or late glacial age. This assessment is supported by the present study, and taken as a basis for further classification. Several observations support this assessment; the glacial fractures deviate in general appearance from fractures classified as older, and also from fractures observed at the other drill sites and Klubbudden (cf Figure A-1).

Table A-1. Drill site 5, fracture distribution with respect to aperture and trace length.

Fracture trace length	Open fractures	Closed fractures	All fractures
Trace length < 50 cm	367	0	367
Trace length > 50 cm	560	353	913
Total	927	353	1280

A significant feature of drill site 5, in relation to the other sites subject to detailed mapping at Forsmark, is that it exhibits many more open fractures. This is the case also when drill site 5 is compared with rock exposures in the Forsmark area in general (Michael Stephens, oral communication). Also, the glacial fractures have larger apertures. Fracture fillings of loose sediments are common at drill site 5, but absent at other sites, except for very superficial parts where root and frost bursting has occurred. In the superficial part of drill site 5, in all 334 unspecified fractures were mapped, 203 of which were open. These were not specified with respect to age and origin, since it could not be determined whether or not open fractures were of glacial age or more recent features caused by frost or plant root bursting.

Old fractures are characterized by being tightly closed. Occasionally they are coated or filled with secondary minerals such as calcite or chlorite. But most of them are too thin to allow identification of any mineral fill or coating. The host rock surrounding many of the older fractures display rock staining, usually 1–2 mm, and sometimes red colouring up to 1–2 cm. Sample tests with diluted hydrochloric acid on a large number of the closed fractures were negative, implying lack of calcite. The quantities of the different types of fractures are shown in Table A-2.

On completion of identification and mapping of 300 glacial fractures, an effort was made to determine whether fractures identified as glacial were reopened older fractures, or if they had been initiated and opened in fresh rock. Some of the fractures were short (5–50 cm) and assessed to cut through fresh rock, with fresh surfaces and no staining of host rock or mineral coatings. These fractures often occurred between longer fractures, interconnecting those. On site, it was therefore decided to conduct the same classification for the remaining 407 glacial fractures. Out of these, 234 featured clear indications of being reopened fractures of old age, as indicated by:

- staining of host rock or mineral coating,
- fracture only partly opened,
- one out of a fracture swarm, with generally closed fractures, often with staining.

For the remaining 173 fractures it was not possible to determine these parameters. On the other hand, none of these fractures could clearly be identified as opened in fresh rock, as was the case with the short fractures mentioned above.

Table A-3 shows aperture data for all fractures documented at drill site 5, grouped in six categories according to observed aperture. 353 were assessed as closed and 927 as open (cf Table A-2). Of the latter, more than 50% displayed apertures less than 1 mm, while a few dominant fractures had very large apertures.

Table A-2. Drill site 5, fractures classified in the present study with respect to age and aperture.

	Open fractures	Closed fractures	All fractures
Glacial fractures	707	0	707
Old fractures	17	222	239
Unspecified fractures	203	131	334
Total	927	353	1280

Table A-3. Drill site 5, observed fracture apertures.

Aperture	Frequency
Closed	353
Up to 1 mm	712
More than 1, up to 10 mm	178
More than 10, up to 50 mm	30
More than 50, up to 100 mm	4
More than 100 mm	3
Total	1280

Few fractures featured visible mineral fill or coating. Exposed surfaces have usually been eroded from any possible coating, and closed fractures are usually too thin for any coating to be visible. Core drillings have been performed to provide samples for determination of such coating or fracture surface staining. Results are reported in Appendix D.

A3 Major glacial fractures

A total of four spectacular glacial fractures or fracture concentrations were identified at the excavated rock outcrop, as shown in Figure A-3 and Figure A-4. These are labeled as follows:

- Pl 1, 5 cm wide fracture with a gentle dip to the southeast, occurring with steeper fractures of the same strike direction.
- Pl 2, 15 cm wide fracture with a gentle dip to the southeast.
- Pl 3, 10 cm wide fracture with a gentle dip to the southeast.
- Pl 4, 2 cm wide fracture with a subvertical dip and 3 cm uplift.

The gently dipping fractures are filled with glacial sediments of various grain size compositions. At Pl 1 the total observed fracture length is more than 10 m, and the subhorizontal fracture seems to be continuous. It is believed to be a reactivation of an older fracture. Several rotational subvertical displacements can be observed, as shown in Figure A-5 to Figure A-8. The surrounding rock is also rich in fractures with trace lengths of 50 cm or less.

The subhorizontal fractures at Pl 2 occur together with vertical fractures, striking NE and NW, thus dividing the rock mass into loose box-shaped boulders as shown in Figure A-9. The fracture at Pl 3 has a trace length of ca 3 m and varies in width from 10 cm in the middle to a few mm towards the ends (Figure A-10). The fill material is silt and sand showing a laminated structure (Figure A-11). Finally, at Pl 4 a relative vertical displacement of 2–3 cm can be observed (Figure A-12) in a NW striking subvertical fracture with 1–2 mm thick coating of crystalline calcite.

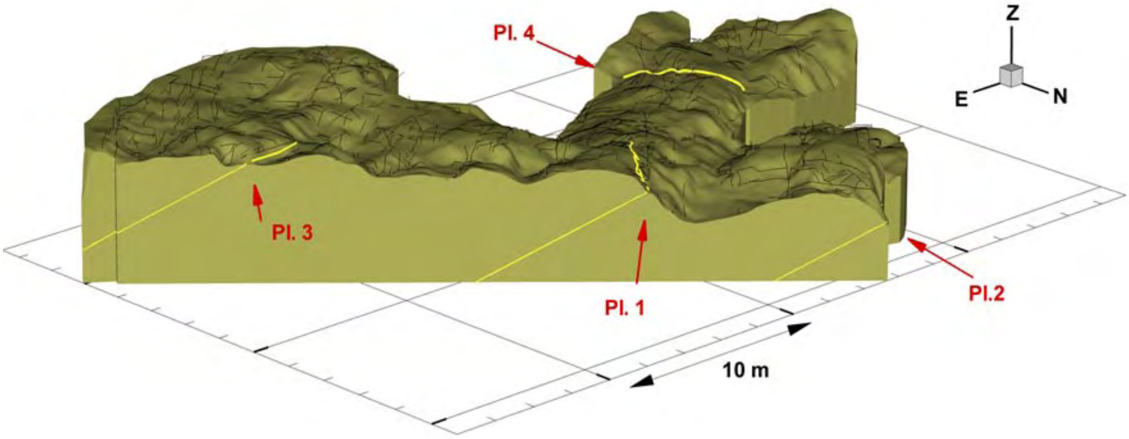


Figure A-4. *Block diagram of drill site 5 at Forsmark, showing the gentle dip of the fractures at locations Pl 1, Pl 2 and Pl 3.*

Figure A-5. *Overview of location Pl 1. The block above the long fracture system stretching from left to right is uplifted and limited by a system of fractures, some subhorizontal dipping southeast, and some subvertical striking northeast. Vertical displacement varies from insignificant to the right (outside the picture), to 20 cm to the left. The centre of rotation for the block is assessed to be just outside the centre of the right edge of the print. Two components contribute to the block movement: upwards translatation (uplift) and upwards-clockwise rotation.*

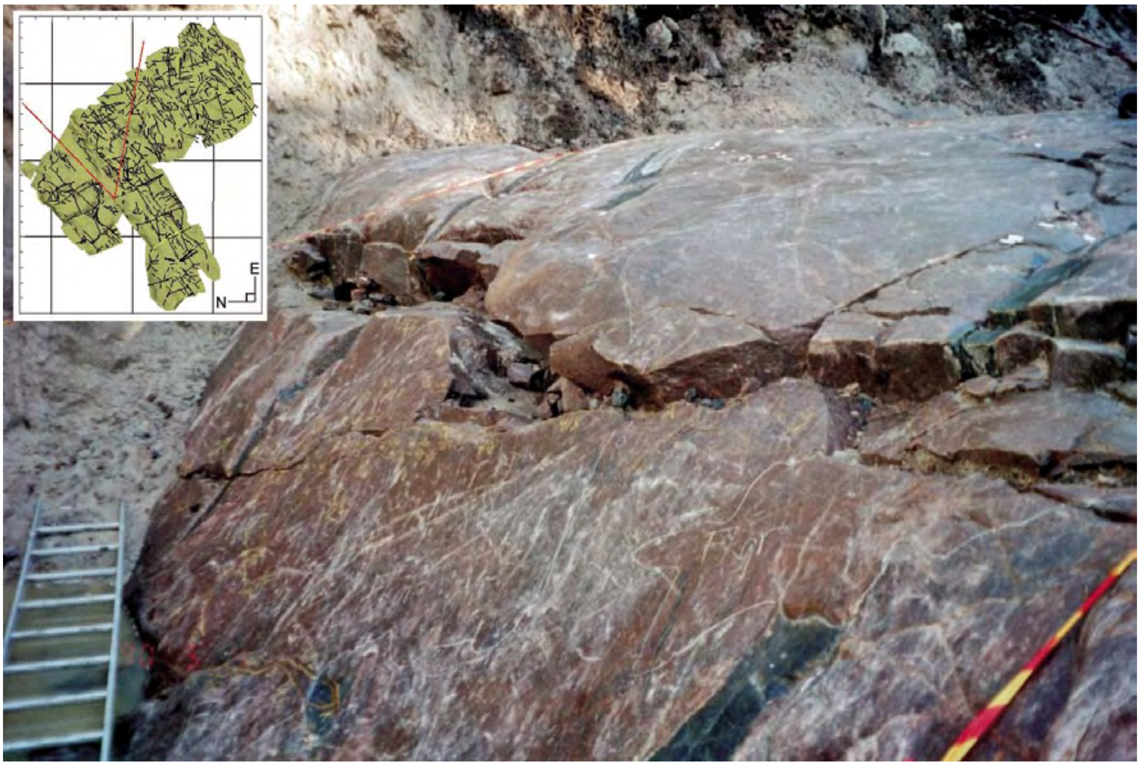


Figure A-6. *View of the longest fracture at Pl 1.*

Figure A-7. *View of fracture system at Pl 1. Vertical displacements vary from zero (front right) over 10–15 cm in several steps (front) to c 20 cm in one step (distant left).*

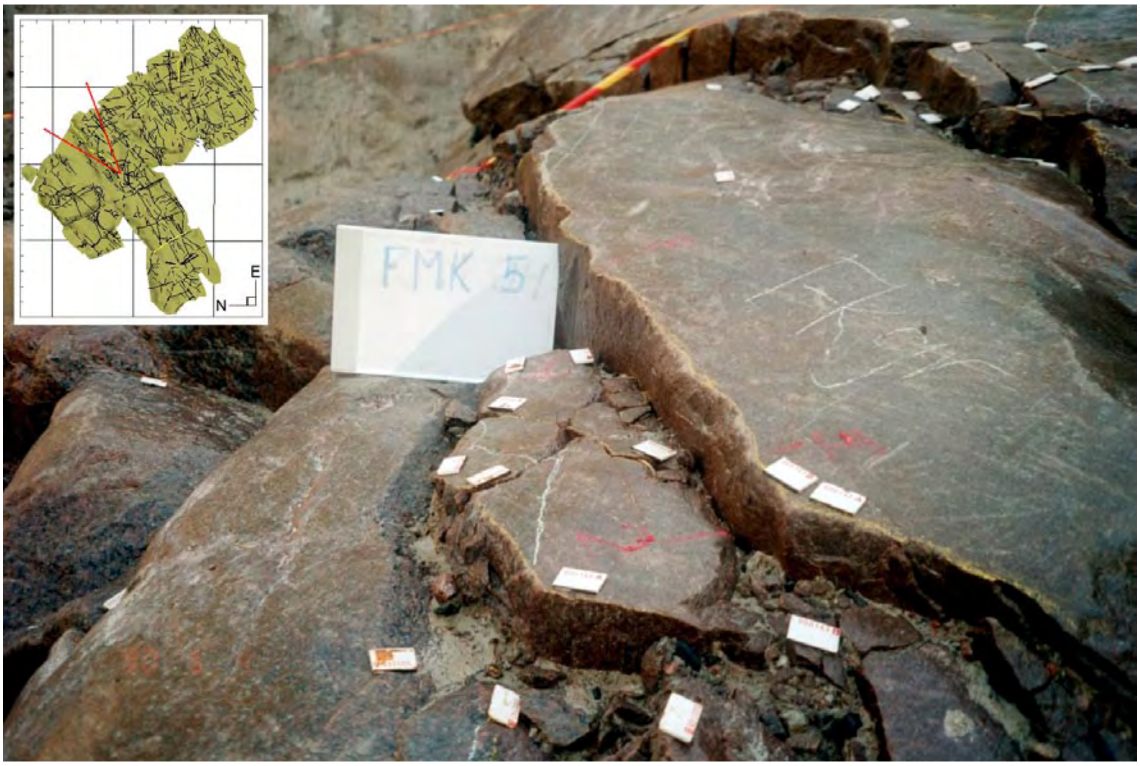


Figure A-8. *Detail of fracture system at Pl 1. The glacially polished surface has been displaced with up to c 15 cm in several steps.*

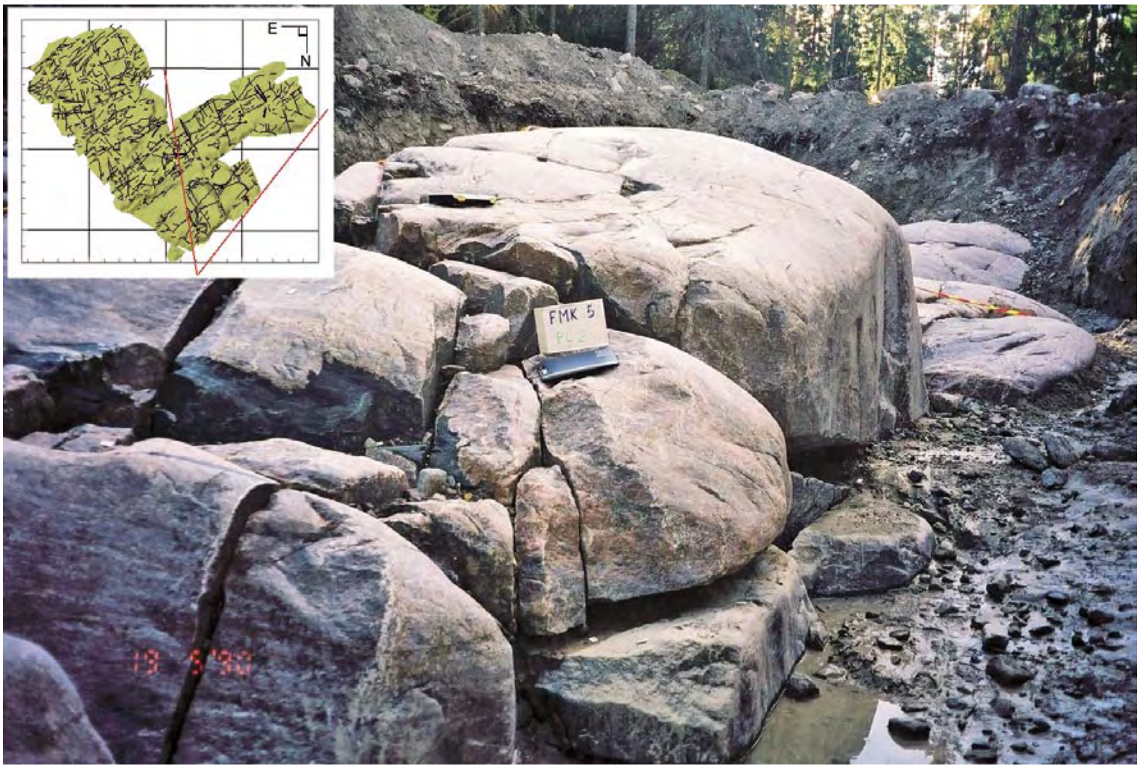


Figure A-9. *Loose blocks at Pl 2. Notice the subhorizontal fractures near the bottom of the pit.*

Figure A-10. *Pl 3. Subhorizontal fracture with sediment fill. Label at right end of fracture.*

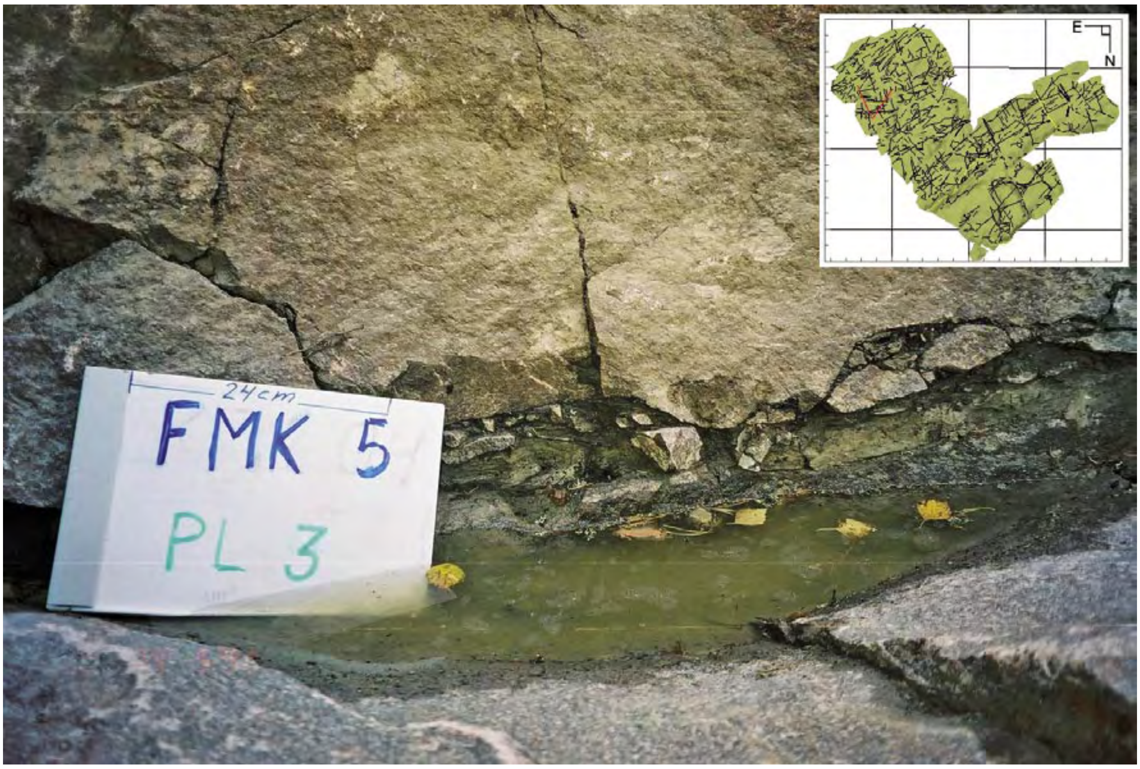


Figure A-11. *Detail of subhorizontal fracture with sediment fill at Pl 3. The sediment infilling is also shown in Appendix G, Figure G-1.*

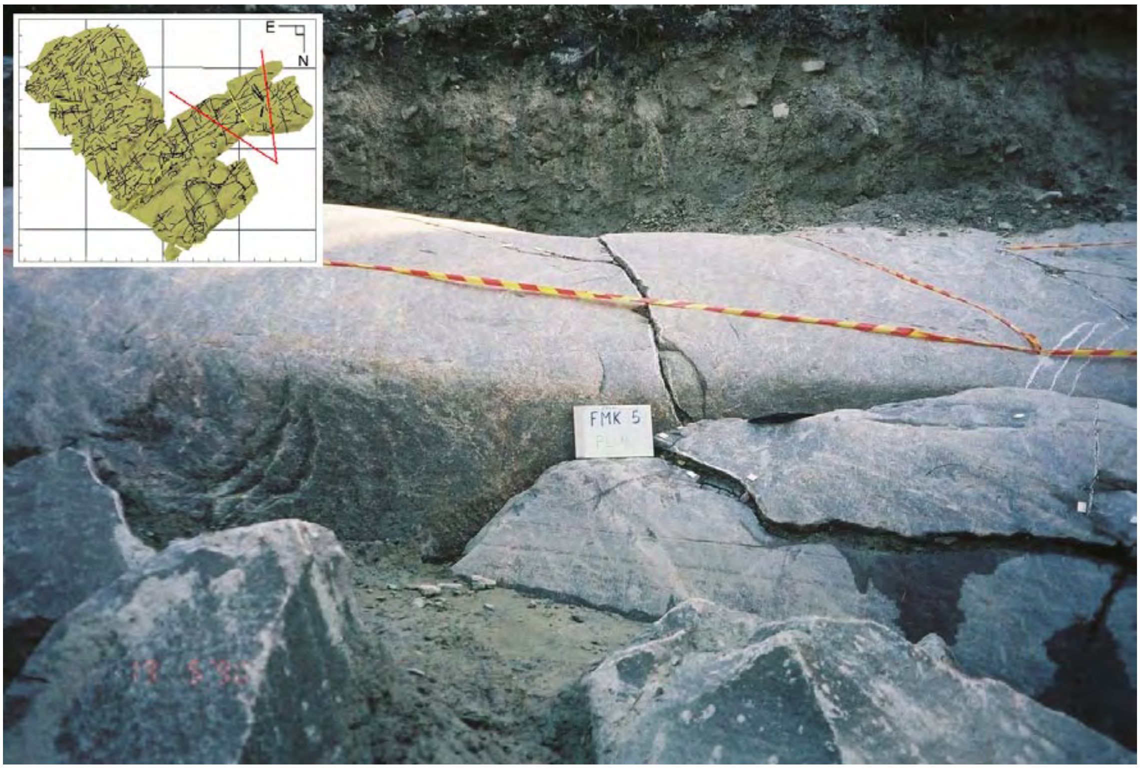


Figure A-12. *Pl 4, the right block features an uplift of 2–3 cm relative to the left block.*

A4 Fracture orientations

Figure A-13 shows a stereographic pole plot contour diagram of fracture orientations at drill site 5. With respect to orientation, most of the fractures can be assigned to three sets:

- Northeast strike, subvertical dip is clearly dominant.
- North-northwest strike, subvertical dip.
- Subhorizontal with gentle dip to the southeast. This set is biased due to the structure of the outcrop, most of its surfaces being horizontal. So, the concentration appears weak in the contour diagram, while the set is clearly visible in the scatter diagram (Figure A-14).

In addition, there are a number of fractures, which usually dip vertically, but with random strikes.

Figure A-15 shows a stereographic contour diagram for fractures classified as older (cf Section A3). The concentration to the three sets is much more distinct for this category than for the total population. Figure A-16 shows a stereographic contour diagram for fractures classified as glacial. The distribution is similar to that of all fractures (cf Figure A-13), but also featuring several pole concentration centres in addition to the general spread. The conclusion is that most of the randomly striking fractures are glacial.

Glacial fractures have been categorized with respect to trace length. Those with trace lengths less than 50 cm (Figure A-17) feature much wider spreading than does the total population of glacial fractures and the entire fracture population (Figure A-13). These short fractures can be regarded to constitute almost the entire random fracture group. Glacial fractures with a trace length of 50 cm or more (Figure A-18) show a similar pattern as the entire fracture population at the site. Fractures classified as reopened (Figure A-19) do not differ from glacial fractures in general (cf Figure A-16).

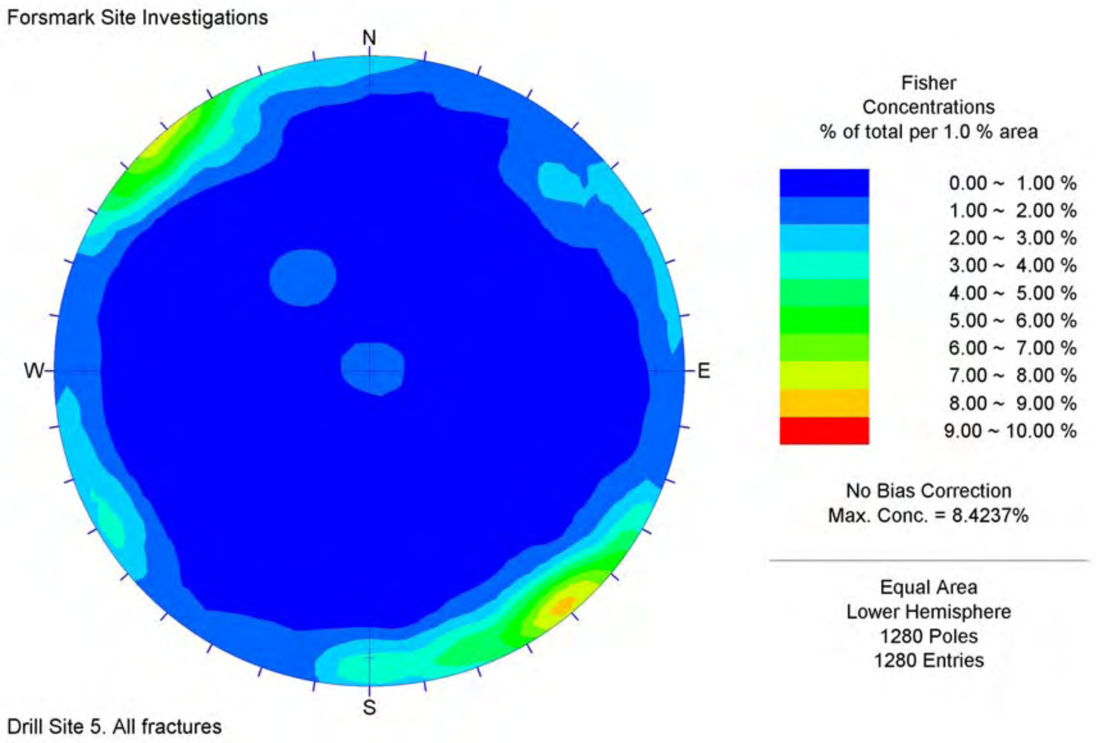


Figure A-13. *Stereographic pole plot contour diagram of all fractures at drill site 5.*

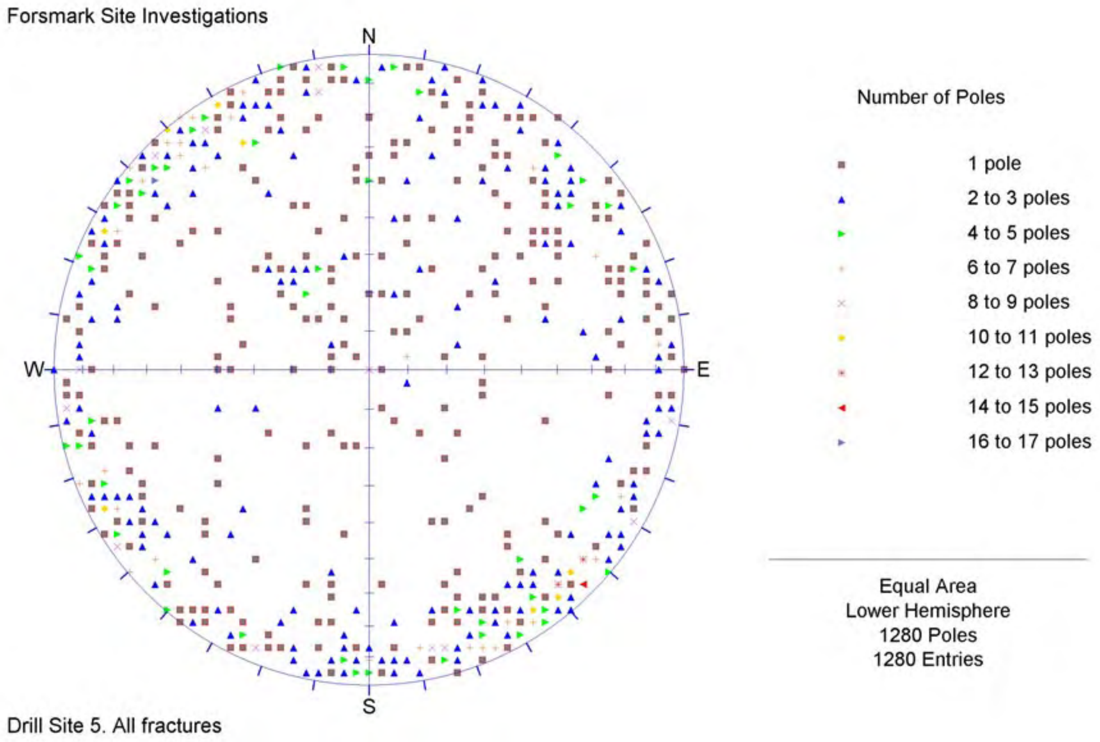


Figure A-14. *Stereographic pole plot scatter diagram of all fractures at drill site 5.*

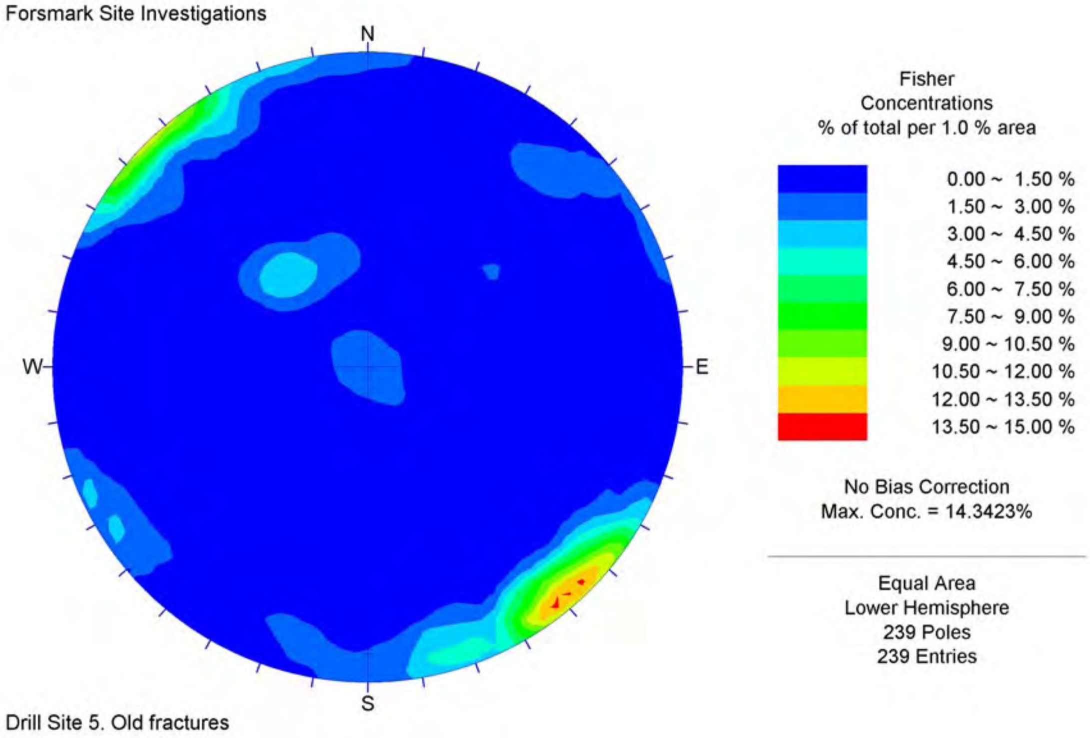


Figure A-15. *Stereographic pole plot contour diagram of older fractures at drill site 5.*

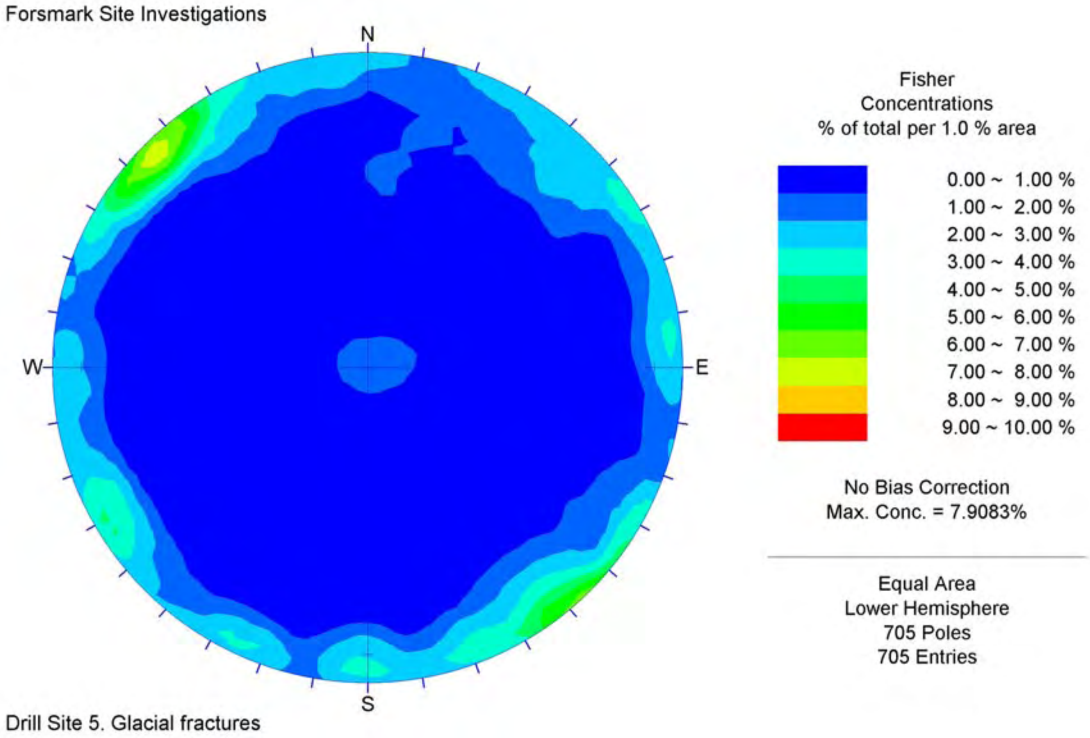


Figure A-16. *Stereographic pole plot contour diagram of glacial fractures at drill site 5.*

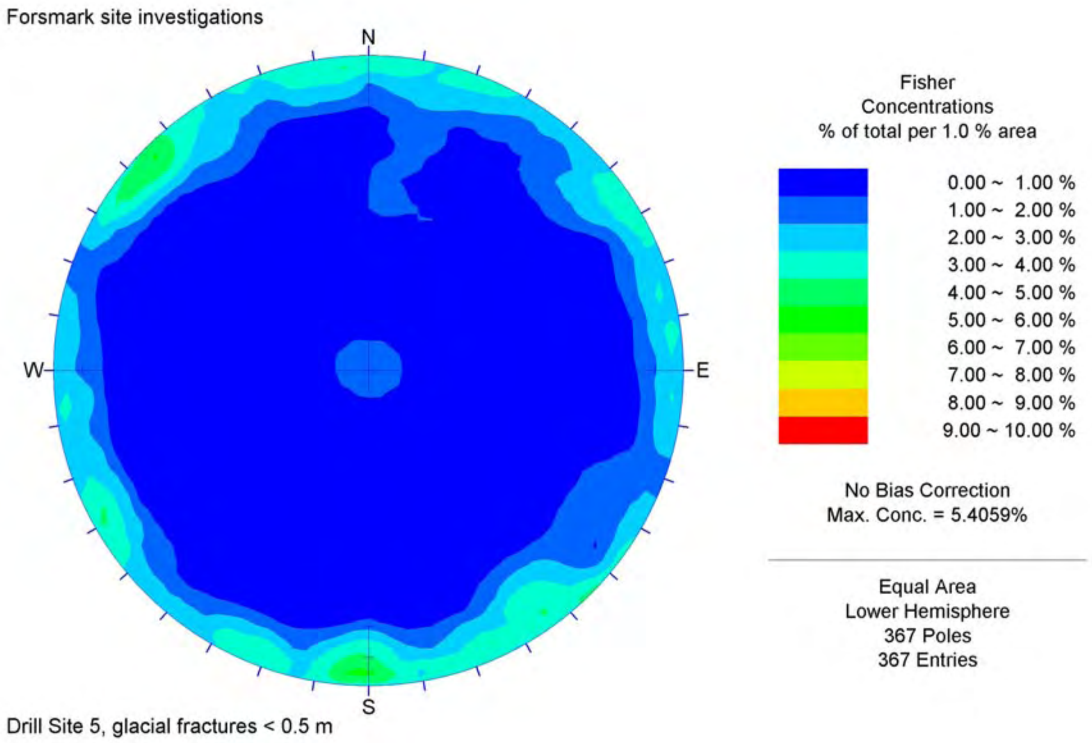


Figure A-17. *Stereographic pole plot contour diagram of glacial fractures with a trace length of less than 50 cm at drill site 5.*

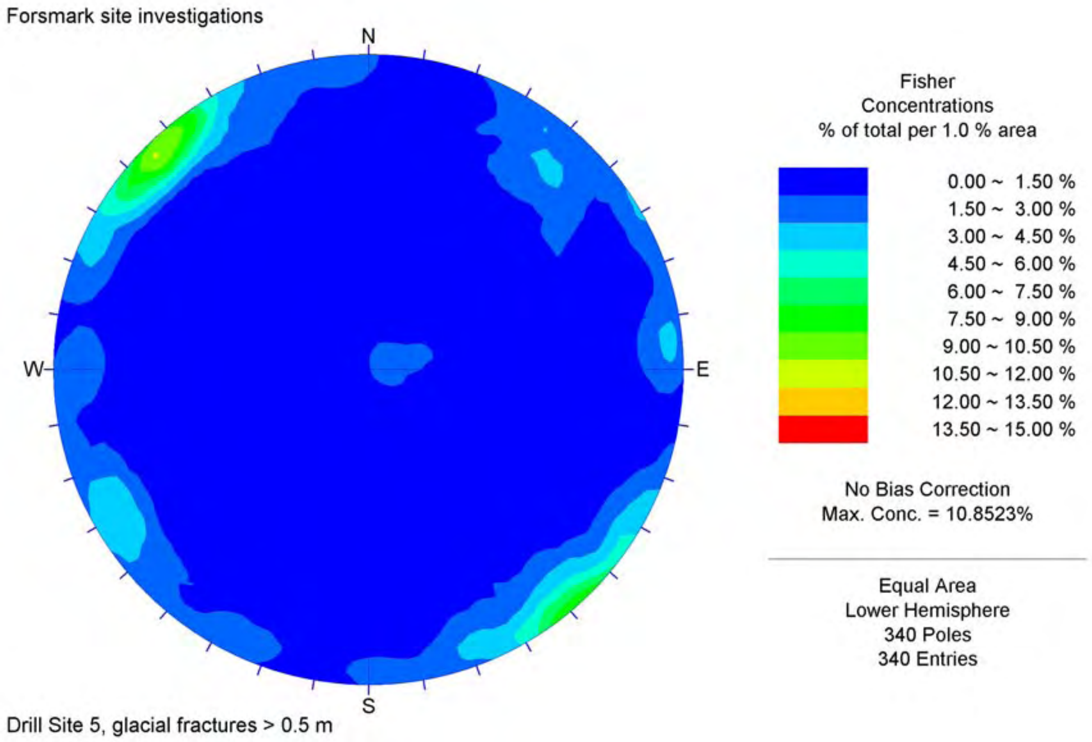


Figure A-18. *Stereographic pole plot contour diagram of glacial fractures with a trace length of more than 50 cm at drill site 5.*

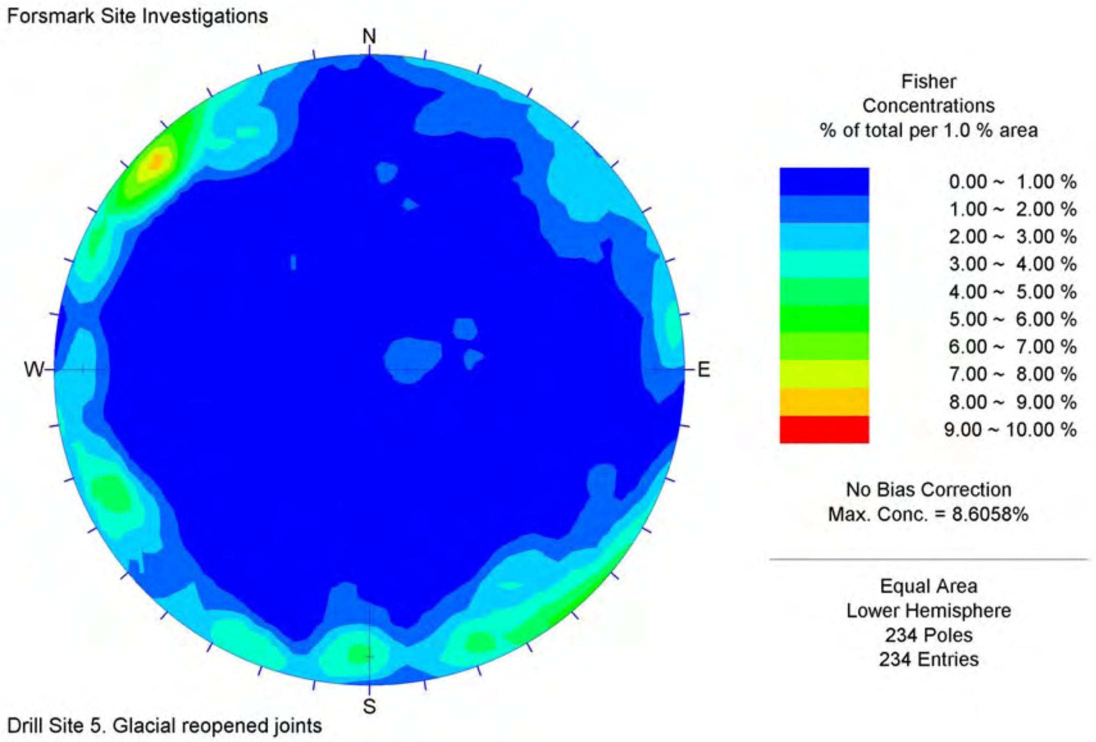


Figure A-19. *Stereographic pole plot contour diagram of glacial fractures which are deemed to be reopened older fractures at drill site 5.*

A5 Comparison with other sites at Forsmark

Pole scatter plots for drill sites 2, 3, 4, 5 and Klubbudden are shown in Appendix A1, Pole contour plots for drill sites 2, 3, 4 and Klubbudden in Appendix A2. Complete strike/dip data can be found in SKB's database SICADA. The mapping of these sites is presented in /Hermanson et al. 2003a, 2003b and 2004/.

Table A-4 compares fracture data from five sites at Forsmark, with respect to quantities of open and closed fractures and relative fracture frequency (fractures per square metre), for fractures with trace length > 50 cm.

Table A-4. Comparison of fracture aperture and fracture frequency at drill sites 2, 3, 4, 5, and Klubbudden.

Site	Area, m^2	Open	Closed	Total fractures > 50 cm	Fractures/m^2
Drill site 2	600	40	946	986	1.6
Drill site 3	550	44	1191	1235	2.2
Drill site 4	525	18	1179	1197	2.3
Klubbudden	325	72	1129	1201	3.7
Drill site 5	501	556	357	913	1.8

The number of open fractures at DS2 is a nominal estimate only. During mapping of the site, 249 fractures were initially assessed to be open, viewed by the unaided eye. However, during subsequent mapping of DS3, DS4 and Klubbudden, occasional rainfalls occurred and a number of depressions on the rock surface were filled with water. A large number of fractures which at first had been assessed as being open did, however, not drain the water overnight, and were therefore reviewed and classified as closed, the opening only affecting the most superficial few centimeters of the fracture. With respect to this, also the amount of open fractures at DS2 was reassessed to be in the same order of magnitude as for the other sites. A nominal estimate of 40 open fractures was assigned to DS2.

Excluding drill site 5, no evidence of glacial fractures has been observed at any of the sites. Open fractures at all other sites are usually just visible. The few exceptions observed feature widths up to some 10 mm. None of these show any displacement, and those with apertures over 1 mm all occur in areas with little soil cover, possibly indicating root or frost bursting. A few of the open fractures may be glacial, but there is no evidence neither to support nor to refute this.

Comparing the pole plot contours from drill site 5 with those of the other sites we find that DS5 deviates from the others by a much wider orientation spread. Drill sites 2, 3, 4 and Klubbudden all feature two or three distinct sets (cf Appendix A2), similar to the older fractures of drill site 5. The subhorizontal set is weak in the contour plots, as few fractures have been mapped (cf scatter plots in Appendix A1), due to the subhorizontal appearance of the outcrop surfaces. The orientations of the sets are summarized in Table A-5. Apart from minor orientation differences and a random set at drill site 2, the overall orientation picture is similar for the sites.

Table A-5. Fracture sets at drill sites 2, 3, 4, 5 and Klubbudden.

Site	NW set	NE set	Subhorizontal	Other sets
Drill site 2	290/90	35/90	10° SE	70/90
Drill site 3	295/85	45/90	10° SE	160/85
Drill site 4	320/80	50/80	5° SE	350/85
Klubbudden	295/85	215/85	5° NE	140/85
Drill site 5	330/85	50/90	10° SE	–

A6 Conclusions

With support from the mapped data the following conclusions have been drawn:

- The general appearance of drill site 5 is obviously different from that of the other mapped sites.
- Open fractures are much more abundant at drill site 5 than at the other sites, the difference being a factor of about 20.
- Defining glacial fractures as the sum of reactivated, old fractures and fractures possibly created during or after glaciation, it is obvious that glacial fractures constitute more than half of the fractures at drill site 5. Of the remaining 203 unspecified open fractures, at least 150 are judged to be glacial.
- Some of the open fractures at the other sites may be glacial, but there are no obvious cases.

- Many of the glacial fractures at drill site 5 with trace lengths less than 50 cm feature rough surfaces with no surface coating or staining, indicating that they are of glacial origin rather than reactivations of existing fractures. There are no such fractures at the other sites, other than at superficial parts, where they have been subjected to frost and root bursting.
- Most of the glacial fractures with a trace length greater than 50 cm are interpreted as reopened old fractures. It is an open question if any of the observed glacial fractures with a length of over 1 m are actually new.

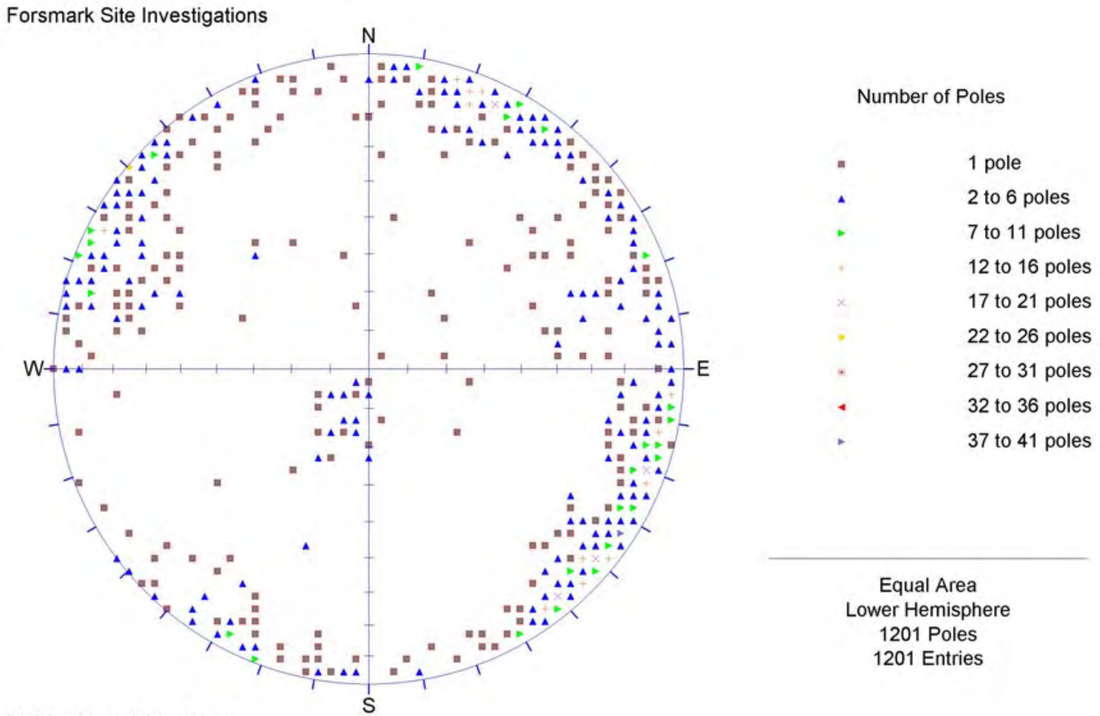
A7 References

Hermanson J, Hansen L, Olofsson J, Sävås J, Vestgård J, 2003a. Detailed fracture mapping at the KFM02 and KFM03 drill sites, Forsmark. SKB P-03-12, Svensk Kärnbränslehantering AB.

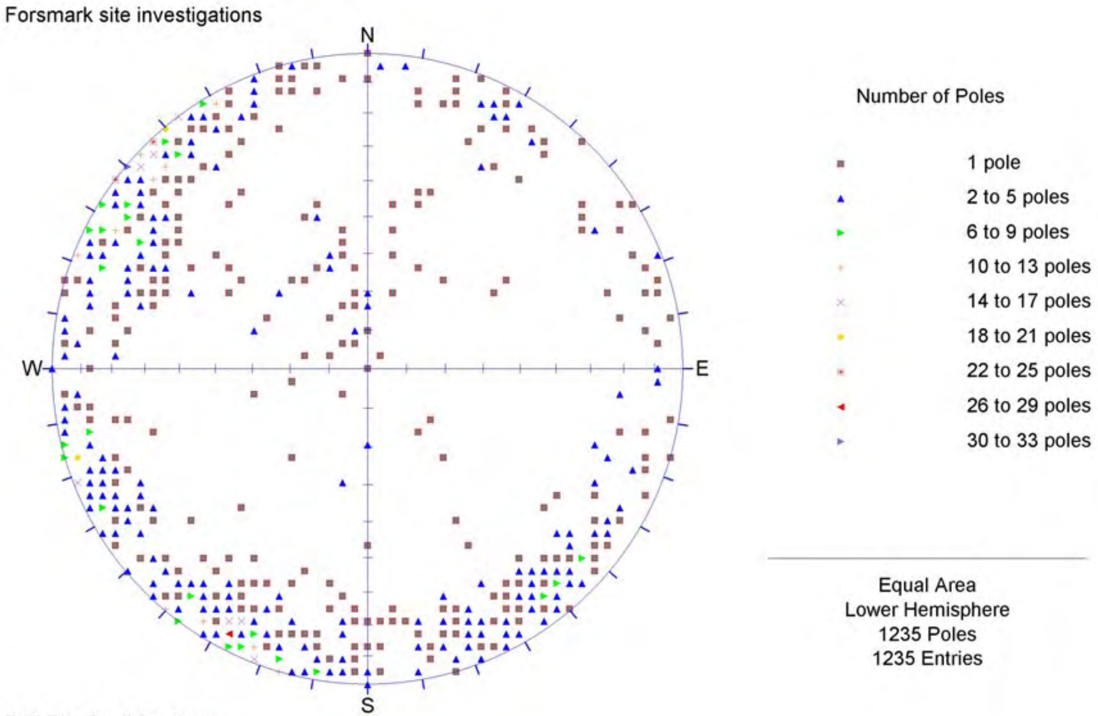
Hermanson J, Hansen L M, Vestgård J, Leiner P, 2003b. Detailed fracture mapping of the outcrops Klubbudden, AFM001098 and Drill Site 4, AFM001097. SKB P-03-11, Svensk Kärnbränslehantering AB.

Hermanson J, Hansen L M, Vestgård J, Leiner P, 2004. Detailed fracture mapping of excavated rock outcrop at Drill Site 5, AFM100201. SKB P-04-90, Svensk Kärnbränslehantering AB.

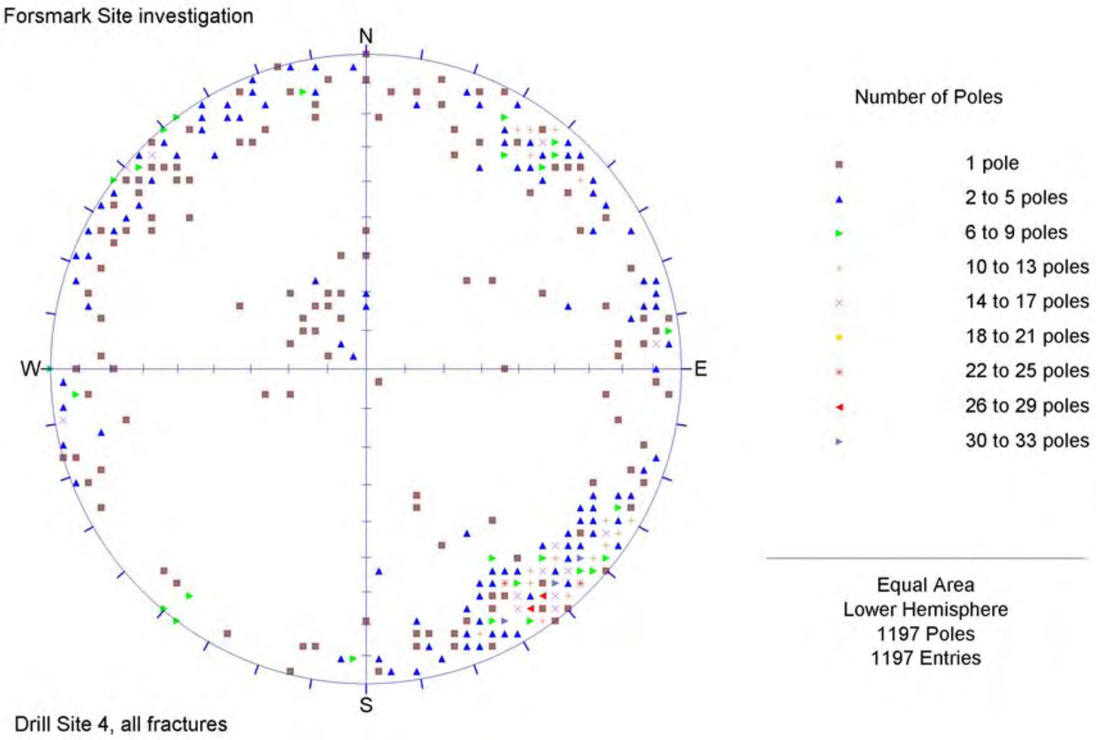
Pole plots of fractures mapped at DS2, DS3, DS4, DS5, and Klubbudden

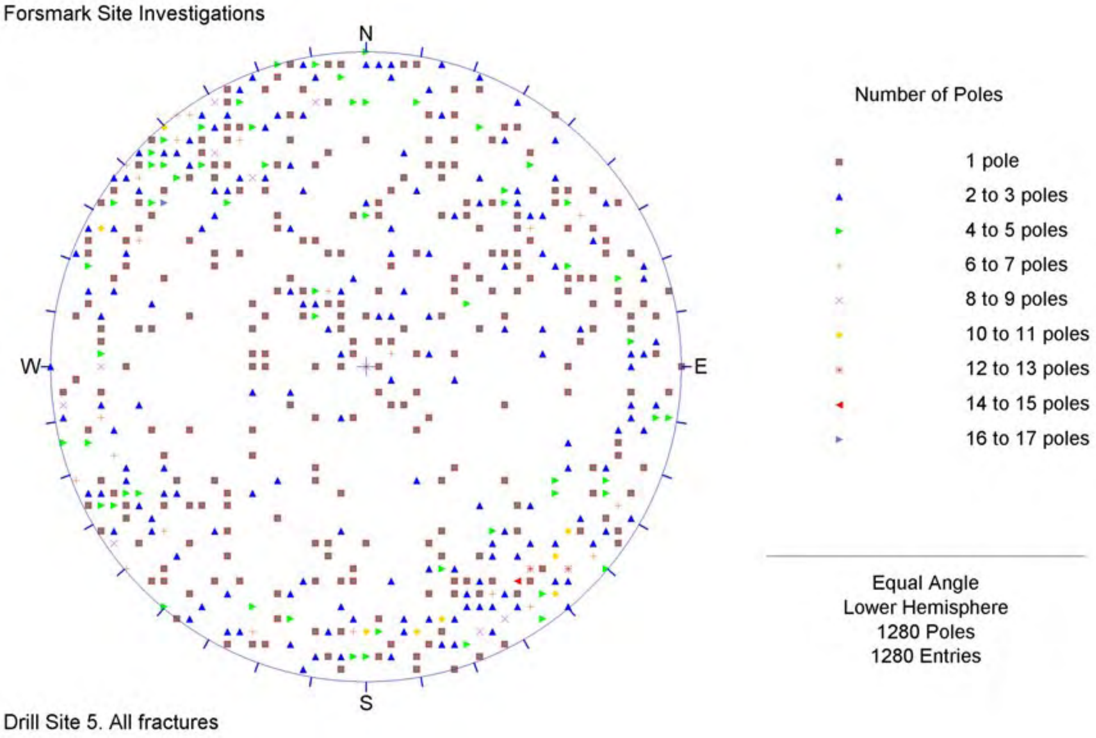


Klubbudden. All fractures



Drill Site 3, all fractures


Forsmark Site investigation
N
E
S
W
Number of Poles
1 pole
2 to 5 poles
6 to 9 poles
10 to 13 poles
14 to 17 poles
18 to 21 poles
22 to 25 poles
26 to 29 poles
30 to 33 poles
Equal Area
Lower Hemisphere
1197 Poles
1197 Entries
Drill Site 4, all fractures


Forsmark Site Investigations
N
E
S
W
Number of Poles
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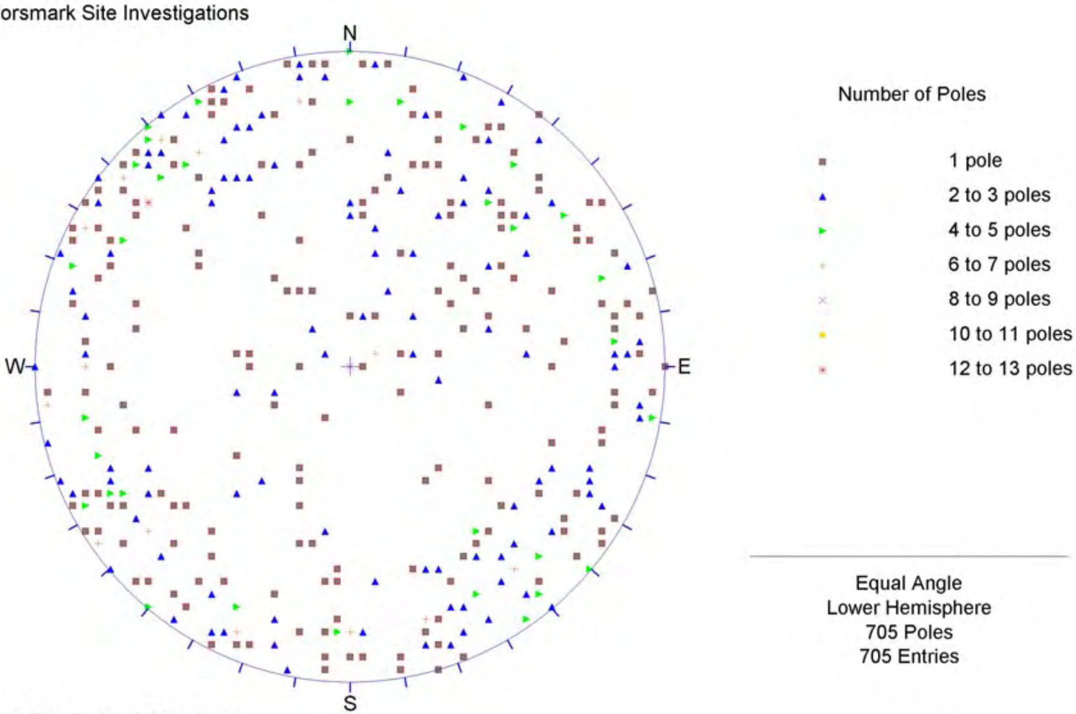
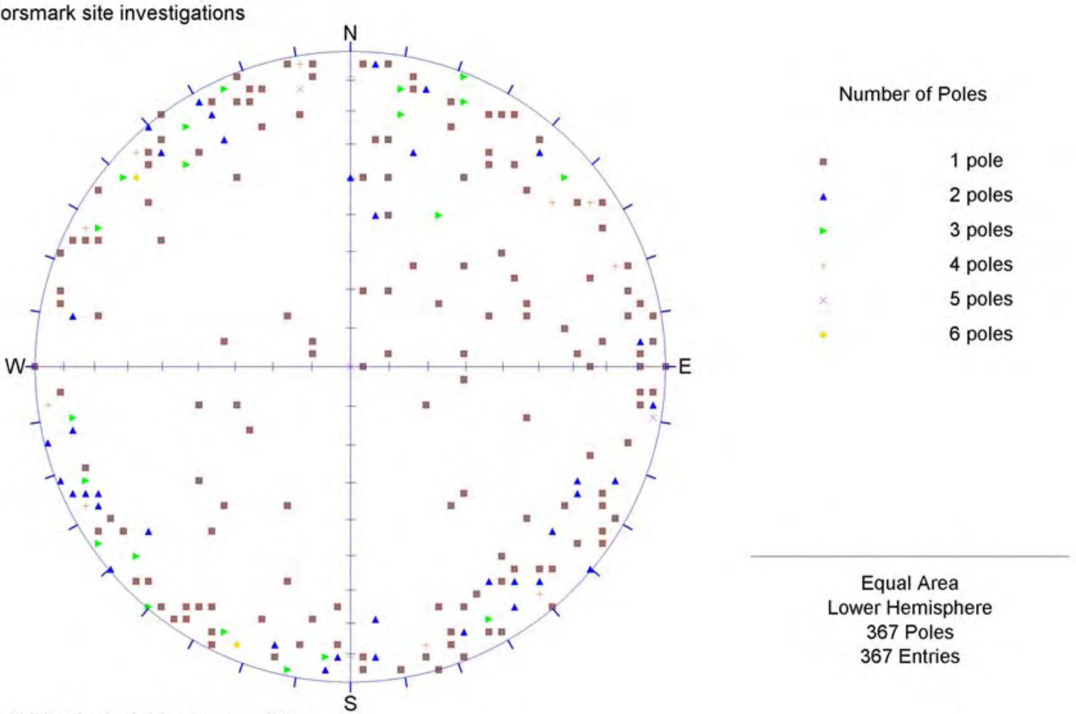
2 to 3 poles
4 to 5 poles
6 to 7 poles
8 to 9 poles
10 to 11 poles
12 to 13 poles
14 to 15 poles
16 to 17 poles
Equal Angle
Lower Hemisphere
1280 Poles
1280 Entries
Drill Site 5. All fractures

Forsmark Site Investigations

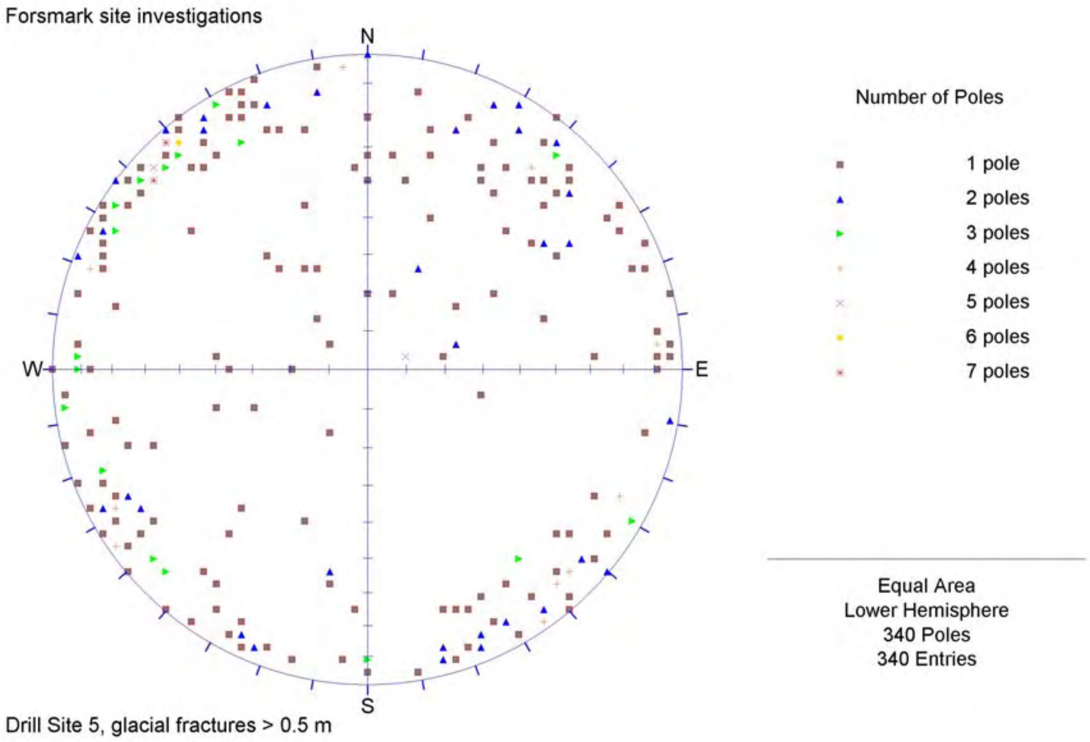


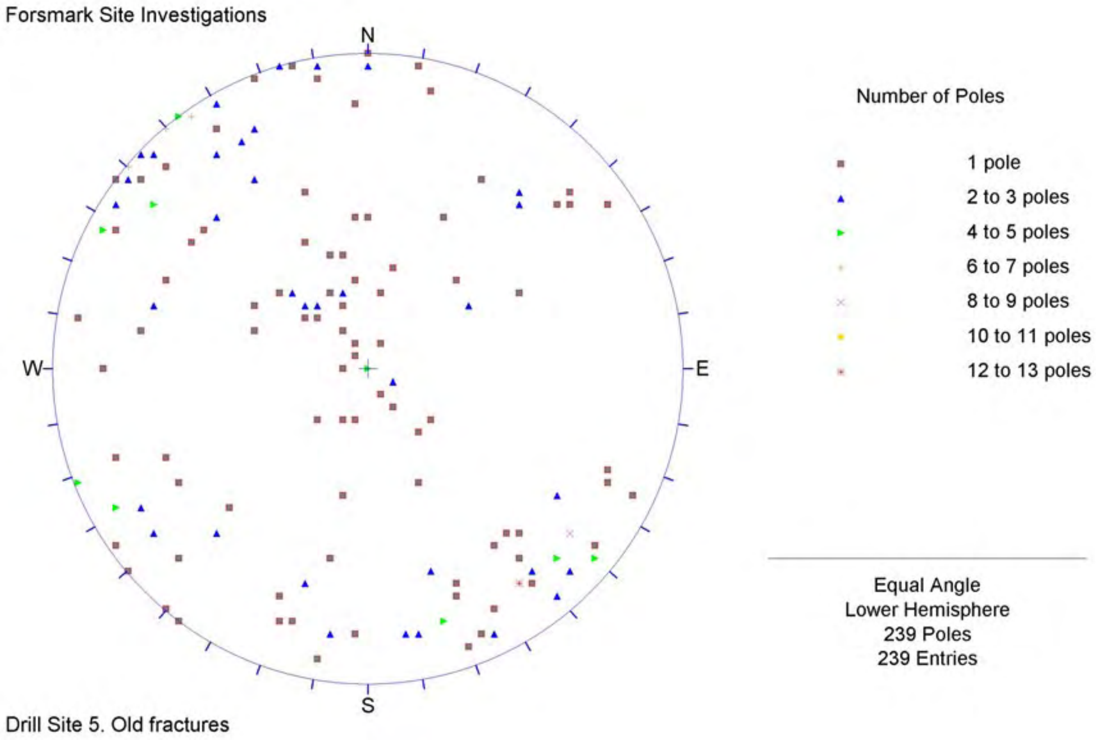
Drill Site 5. Glacial fractures

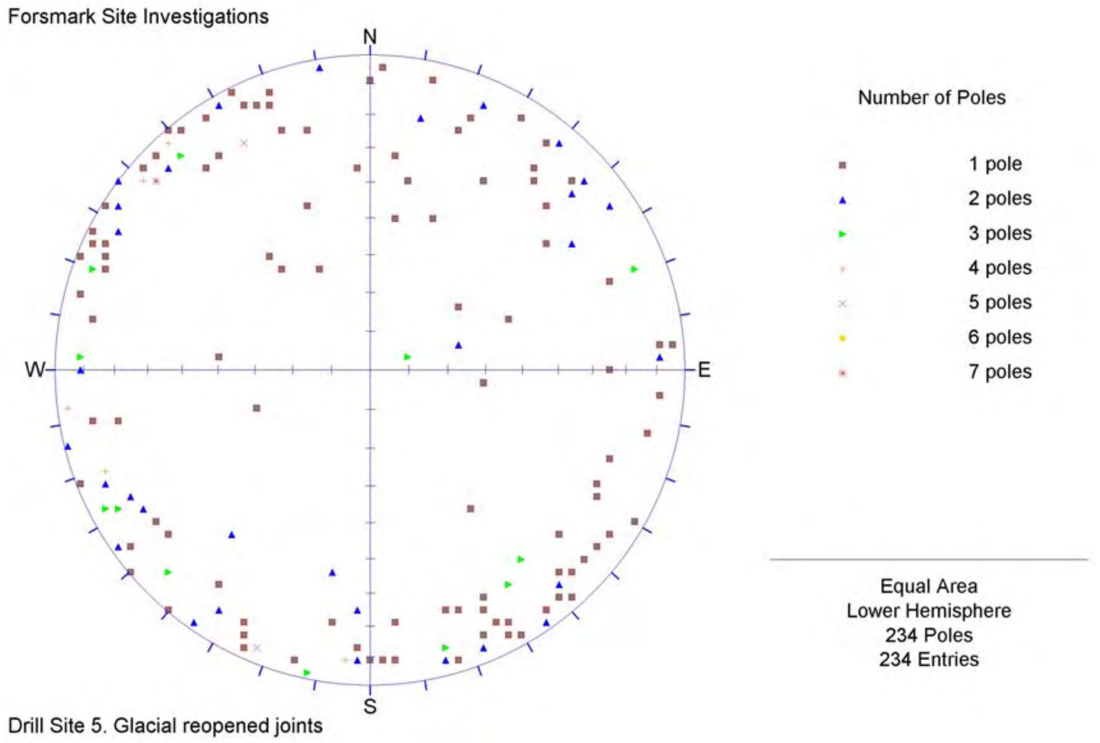
Forsmark site investigations



Drill Site 5, glacial fractures < 0.5 m


Forsmark site investigations
N
W
E
S
Number of Poles
1 pole
2 poles
3 poles
4 poles
5 poles
6 poles
7 poles
Equal Area
Lower Hemisphere
340 Poles
340 Entries
Drill Site 5, glacial fractures > 0.5 m


Forsmark Site Investigations
N
W
E
S
Number of Poles
1 pole
2 to 3 poles
4 to 5 poles
6 to 7 poles
8 to 9 poles
10 to 11 poles
12 to 13 poles
Equal Angle
Lower Hemisphere
239 Poles
239 Entries
Drill Site 5. Old fractures


Forsmark Site Investigations
N
W
E
S
Number of Poles
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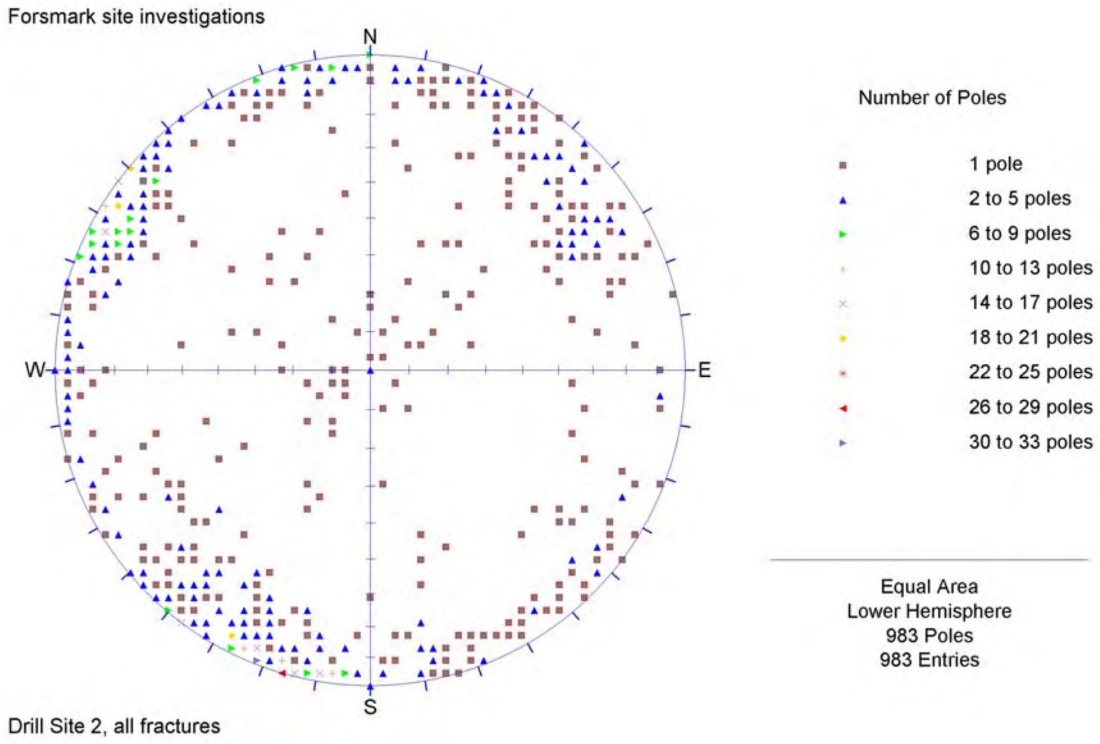
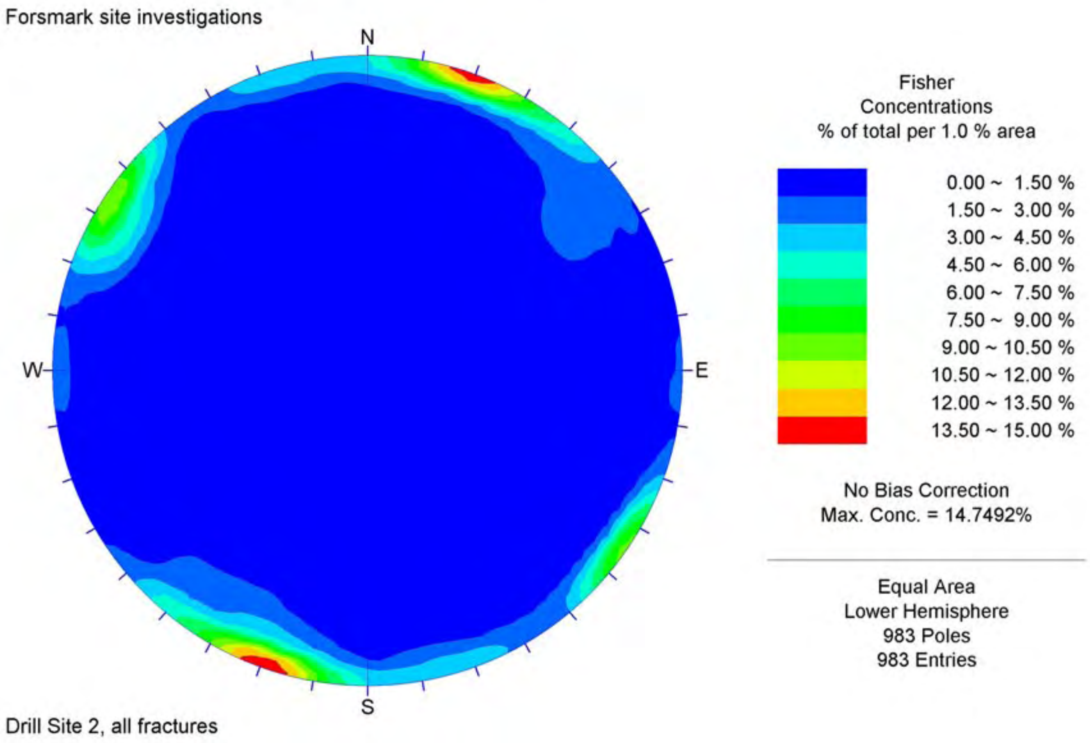
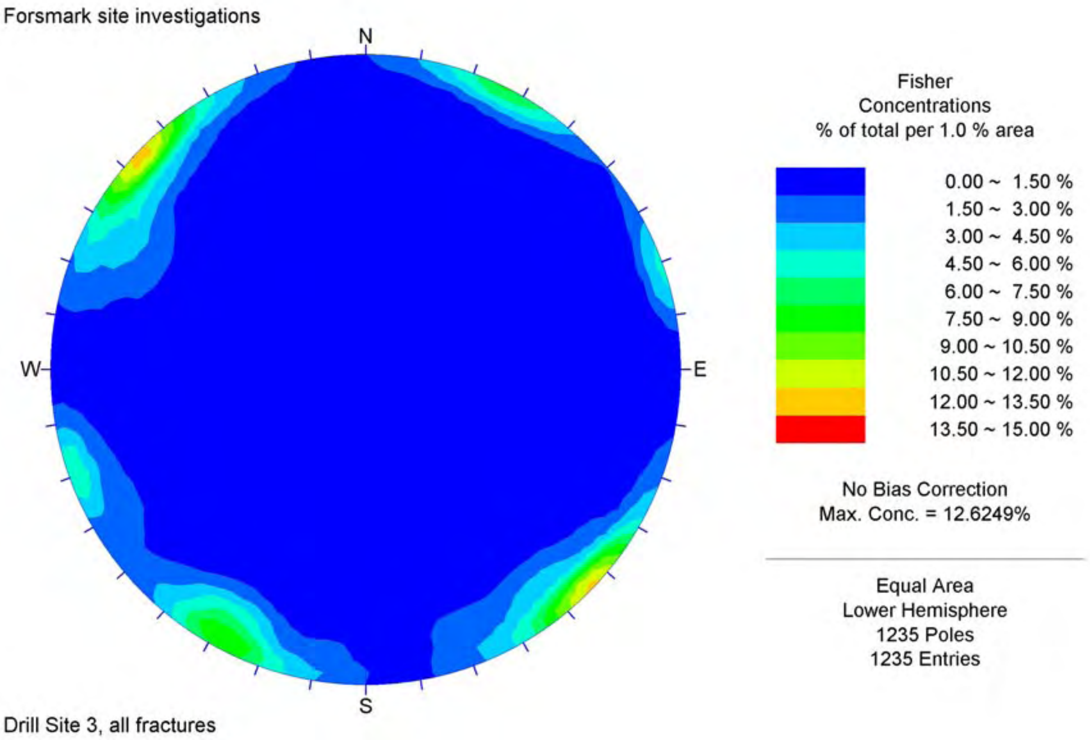
2 poles
3 poles
4 poles
5 poles
6 poles
7 poles
Equal Area
Lower Hemisphere
234 Poles
234 Entries
Drill Site 5. Glacial reopened joints

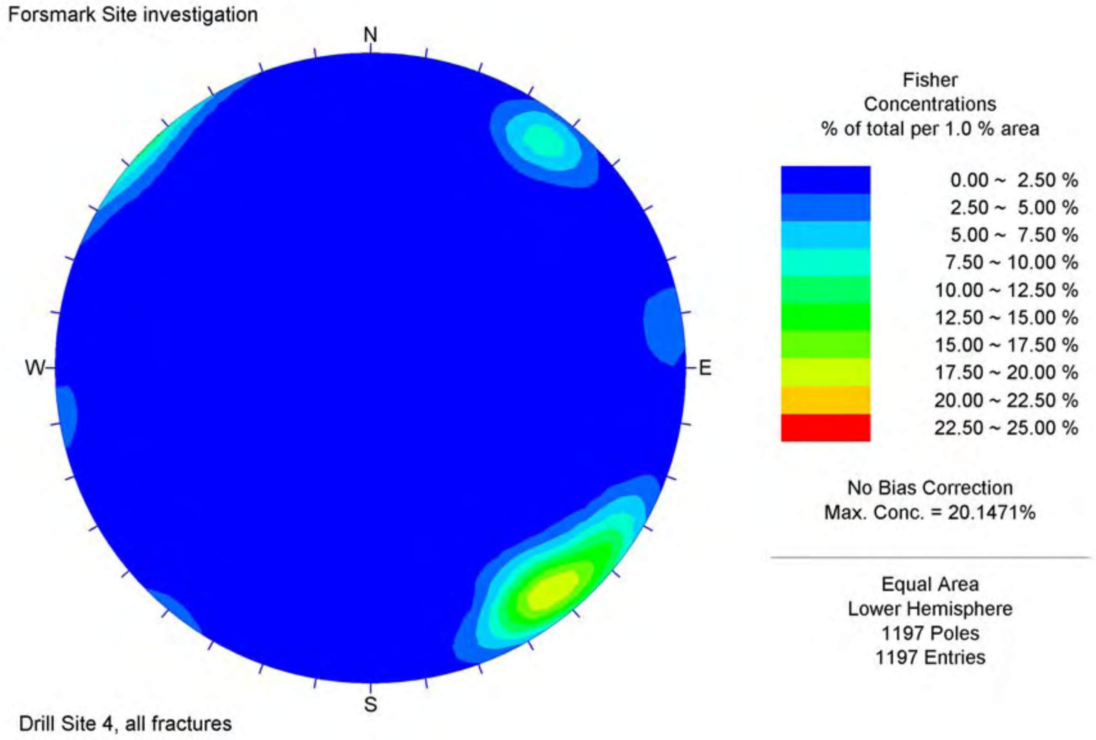

Forsmark site investigations
N
W
E
S
Number of Poles
1 pole
2 to 5 poles
6 to 9 poles
10 to 13 poles
14 to 17 poles
18 to 21 poles
22 to 25 poles
26 to 29 poles
30 to 33 poles
Equal Area
Lower Hemisphere
983 Poles
983 Entries
Drill Site 2, all fractures

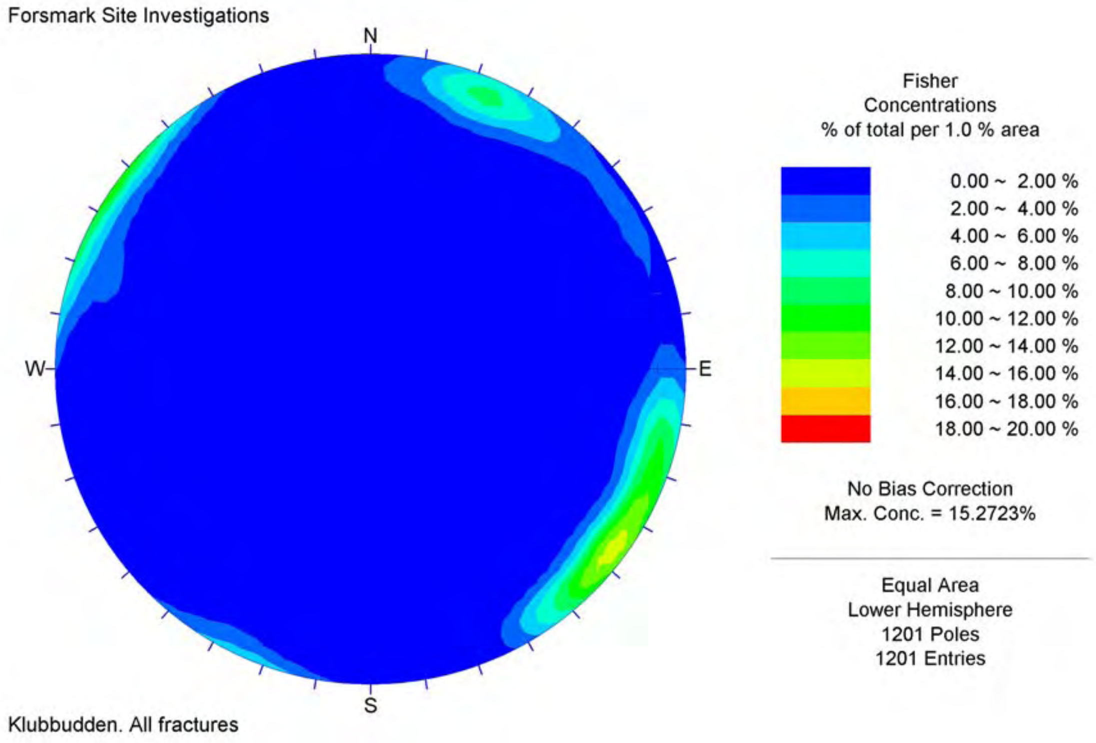
Appendix A2

Pole plot contours of fractures mapped at DS2, DS3, DS4, and Klubbudden






Forsmark Site investigation
N
E
S
W
Fisher
Concentrations
% of total per 1.0 % area
0.00 ~ 2.50 %
2.50 ~ 5.00 %
5.00 ~ 7.50 %
7.50 ~ 10.00 %
10.00 ~ 12.50 %
12.50 ~ 15.00 %
15.00 ~ 17.50 %
17.50 ~ 20.00 %
20.00 ~ 22.50 %
22.50 ~ 25.00 %
No Bias Correction
Max. Conc. = 20.1471%
Equal Area
Lower Hemisphere
1197 Poles
1197 Entries
Drill Site 4, all fractures


Forsmark Site Investigations
N
E
S
W
Fisher
Concentrations
% of total per 1.0 % area
0.00 ~ 2.00 %
2.00 ~ 4.00 %
4.00 ~ 6.00 %
6.00 ~ 8.00 %
8.00 ~ 10.00 %
10.00 ~ 12.00 %
12.00 ~ 14.00 %
14.00 ~ 16.00 %
16.00 ~ 18.00 %
18.00 ~ 20.00 %
No Bias Correction
Max. Conc. = 15.2723%
Equal Area
Lower Hemisphere
1201 Poles
1201 Entries
Klubbudden. All fractures

Appendix B

Documentation of glacial sediments, fractures and glacial striae at drill site 5

Hanna Lokrantz, Joachim Albrecht
Geological Survey of Sweden (SGU)

June 2004

Abstract

At drill site 5 (BP 5), an investigation of glacial sediments, glacial striae and fractures in the bedrock was performed. The fractures in the bedrock are to a large extent formed during the Late Quaternary. Pre-existing fractures have become reactivated. The tectonic process behind and the extent of the fractured bedrock are still speculative. At least the upper portion of the glacial sediments (mainly till) was deposited by an ice moving from the north. The sediment within the fractures contains re-deposited pollen and was deposited subglacially under quiet sedimentary conditions.

Contents

B1 Introduction

This document reports part of the data gained in *Searching for evidence of late or post-glacial faulting in the Forsmark region*, which is one of the activities performed within the site investigation at Forsmark. The work was conducted according to the method description MD 133.001 and integrated with activity plan AP PF 400-03-20. No deviations from these controlling documents were encountered. Data have been delivered to SKB's data base SICADA, where they are available by the activity plan number.

During the preparatory excavation of overburden and clearing of the rock surface at drill site 5, one of the planned deep core drilling sites, the exposed bedrock proved to be heavily fractured. Some of the fractures were filled with glacial sediment. This occurrence of sediment-filled fractures made it urgent to execute a detailed investigation of the bedrock and the adjacent Quaternary sediments.

B2 Objective and scope

The aim of this investigation was to determine the timing of the fracturing observed at drill site 5, and also the filling of some fractures with soft sediments. It was also intended to contribute to the knowledge about possible causes of the phenomena. This required the documentation and classification of the discovered fractures (including pollen analyses on sediment within the fractures), the documentation of the bedrock surface in terms of glacial abrasion and striation, and finally the documentation and interpretation of the glacial sediments in terms of till genesis and ice movement directions. Field work was carried out by the authors during October 2003, pollen analyses by Ann-Marie Robertsson at Stockholm University (see also Appendix C). Mineral analyses on fracture surfaces were performed by Björn Sandström, Earth Sciences Centre, Gothenburg University, and Eva-Lena Tullborg, Terralogica AB (see also Appendix D).

B3 Site description

The exposed bedrock outcrop is divided into three parts, one large (area I, 20×25 m) in the SE (Figure B-1), one minor (area II, 7×8 m) in the NW and a third, situated W of part I. Areas I and II are separated from each other by a sediment-filled depression. Area III was the last to be uncovered and is only described briefly here. Before stripping, the ground surface was rather flat and almost horizontal, but the bedrock morphology proved to be more pronounced. Generally, the bedrock surface dips gently towards NW. To the NW of area I the bedrock surface dips steeply (strike 230°, dip 50°). The SE part of area I had not been covered by glacial sediments, the NW part and the area II were covered by approximately 1.5 m to 2.5 m of glacial sediments. Between both areas sediment thickness reaches more than 3.5 m. Dominating rock types are fine-grained to medium-grained granites with a few amphibolite dykes.

The bedrock is generally heavily fractured, except the central part of the large outcrop, where the fracture frequency is somewhat lower. In the SE, where the bedrock had been exposed to weathering before stripping, roots and frost activity have over-accentuated the original fracture pattern. This area was excluded from investigation and interpretation. The extent of the fresh-looking fractures is not known, since they occur all over the exposed bedrock and show no signs of ceasing in any direction.

B4 Execution

Sketches of the bedrock surface were made, where different types of fractures were distinguished. Two main criteria were used: openness and glacial abrasion. Open fractures could either be sediment-filled or not. For presentation, data from the present study were plotted into a fracture map of the site produced by Lars Hansen and his co-workers at Golder Associates AB (see Appendix A). Small drill cores were taken over certain fractures with a hand-held rock core drill. Furthermore, the pattern of glacial abrasion on the exposed bedrock was documented in order to recover information about glacial behaviour and ice flow directions. Adjoining excavated sections with glacial sediments were cleaned with shovels, scrapers etc, their lithology and structures were described and a local till stratigraphy was established.

Fractures, polished bedrock and sediment sections were photo-documented. Two clast fabric analyses were carried out using a knife and a compass (360°) with inclinometer to identify preferred clast orientations /cf Dowdeswell and Sharp, 1986/ and eventually find out if the glacial sediments were deposited during the same glacial event that caused the polishing and fracturing of the bedrock. Fabric analyses were made on 25 clasts with a/b ratio > 3:2 and results were plotted in lower hemisphere stereographic Schmitt nets. Sediment samples were taken from diamictic fracture fillings and till for petrographical analyses as well as from fractures with fine grained sorted sediments and lenses of silty material till for biostratigraphical analyses.

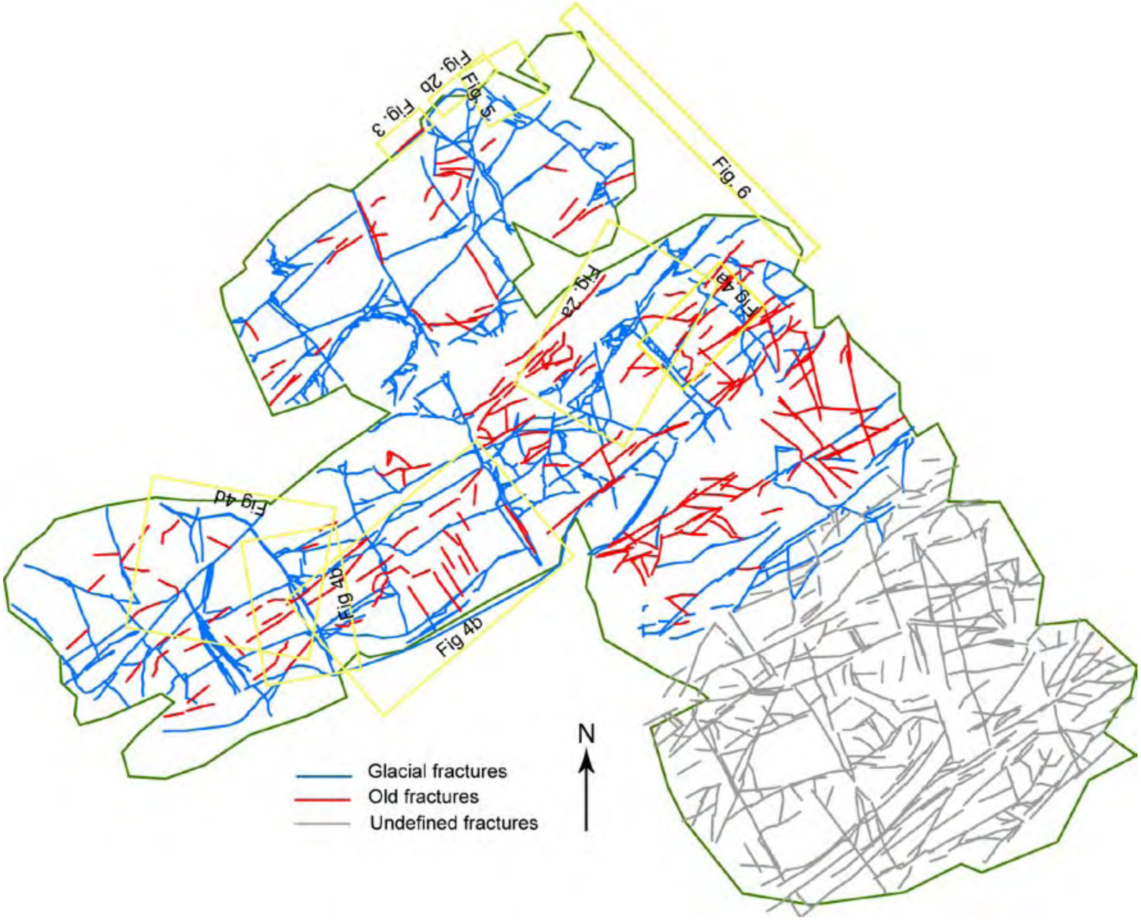


***Figure B-1.** Fracture data as reported in Appendix A displayed on a map of the exposed rock surface at drill site 5. Yellow symbols indicate locations of objects shown in figures with numbers as indicated.*

B5 Results

Fractures: The main fracture system strikes 45° (Figure B-2). Many of the fractures in this system dip steeply (c 90°) and are open (1–2 mm) and do generally not expose signs of glacial abrasion. Relative vertical movement of 2–3 cm has occurred in some places, e.g. in the SW part of the outcrop. Some other fractures in the main fracture system (MFS) appear to dip gently, although the exact dip is difficult to determine, because these fractures are filled with up to 20 cm sediment. The outer part of these fillings consists of diamicton (unsorted sediment) and crushed bedrock, giving the sediment a coarse appearance (Figure B-3), whereas the inner parts of the sediment-filling consist of laminated silt and fine sand (Figure B-4) with occasional diamictic lenses. At least in some of these open fractures a reverse movement with displacements of approximately 10 cm has occurred (e.g. Figure B-3a). A set of these fractures forms a pop-up structure, whose upper part seems to have rotated (Figure B-3a). The up-lifted bedrock clasts show a varying degree of glacial abrasion. Another fracture system strikes approximately 140°, perpendicular to the main fracture system, and dips steeply (90°). These fractures often appear to be fresh, without signs of glacial abrasion (Figure B-5a and b). Many of them seem to be reactivations of an older system. In the NW this system consists of open sediment-filled fractures (10 cm wide), with slight signs of glacial abrasion. Freshly looking fractures of various orientations and in some cases showing vertical displacement of up to 4 cm occur at several places at the site (Figure B-5c and d). They sometimes partly occur as reactivations of older systems, but then take a new course in any direction (Figure B-5d). Although most of the displacement is vertical and reverse, some dislocated and rotated bedrock boulders at the NW show a strike slip movement. This is especially distinct, where an amphibolite dyke is cut (Figure B-6).

Microscopic analysis of the fractures (Appendix D) showed that some fractures are fresh and unweathered with occasional recent calcite precipitiations from meteoric water. Other fracture surfaces expose quartz crystals, indicating that these fractures were already existent before the last ice age and may have been reactivated.

Figure B-2. *Overview of the SE outcrop. The hatched line points out the orientation of the main fracture system. View towards SE.*

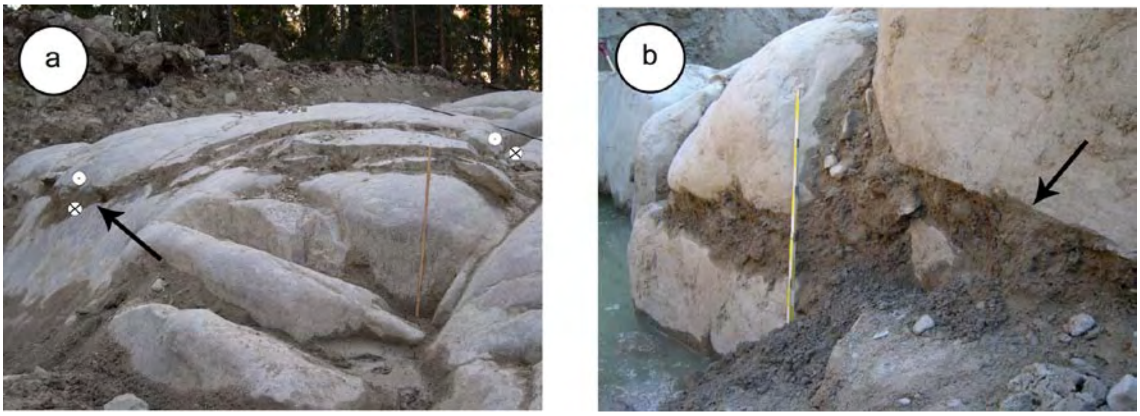


Figure B-3. *Horizontal to gently dipping sediment filled fractures with till in the outer parts. a) fracture in the NW part of the SE outcrop. The vertical displacement is approximately 10 cm and the relative movement is indicated by upwards (point) and inward (cross) going arrows. b) fracture in the NW part of the outcrop.*

Figure B-4. *Laminated silt in a fracture in the NW part of the whole outcrop. The outer part of the sediment fill, which consisted of till, has been removed (cf Figure B-2b).*

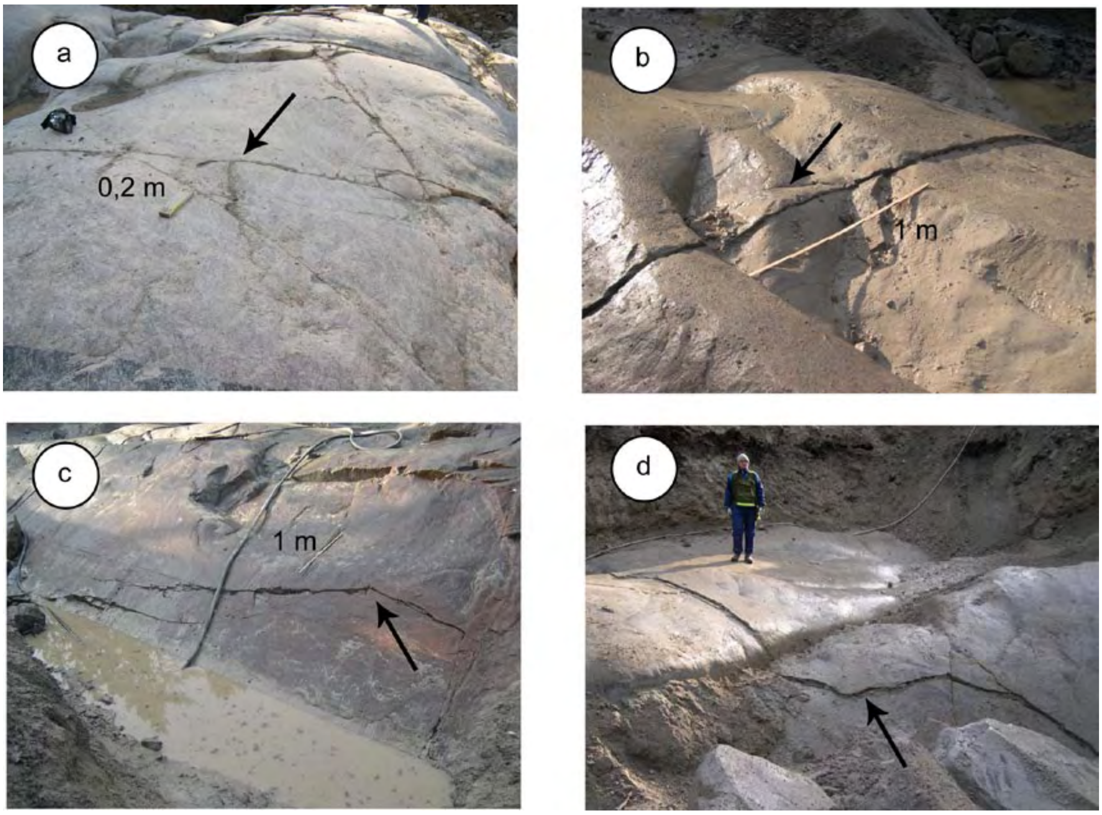


Figure B-5. *Fractures that appear to be fresh without signs of glacial abrasion. a) and b) fractures orientated perpendicular to the main fracture system (cf Figure B-1). Both views towards WSW. c) fracture without any particular orientation. View towards NW. d) the same fracture as in Figure b, but it has taken a new course. View towards SSW.*

Figure B-6. *Fracture showing a strike-slip movement. View towards NE.*

Glacial striation: Glacial striae were found all over the outcrop on both stoss sides and lee sides. Three sets of glacial striae were observed. The dominating set occurs all over the exposure and consists of 1–10 mm thin striae, orientated approximately 360°–180°. It is accompanied by chatter marks and crescentic fractures, indicating an ice flow direction from N. Several lee-side facets on the bedrock surface expose an older and different kind of glacial polish. These facets are characterised by a smooth surface. A secondary set of striae, occurring only on these facet surfaces, is orientated approximately 320°, implying an older ice flow direction from NW. A third set of striae is scant and only weakly developed. It occurs on main surfaces and on facet surfaces. Single striae are 0.5 to 1 cm thick and orientated 20°, indicating an ice flow direction from NNE.

Glacial sediments: Investigation of the northeastern wall cut (orientated 140°, Figure B-7a) revealed two main lithological till units, from bottom to top informally named unit A and unit B. Unit A (Figure B-7b) is a sandy, matrix-supported diamicton with few bedrock clasts. It contains decimetre- to metre large deformed intraclasts of sorted sand and silt and has a close resemblance of a deformation till. Its upper contact to unit B is gradual and coincides approximately with the bedrock surface in the SE part of the section. One clast fabric analysis conducted just above the bedrock surface yielded no preferred orientation of clasts (Figure B-7c). At two localities sorted sand occurs in connection to the fractures in the bedrock (Figure B-7d). Unit B (Figure B-7e) is a sandy and mostly matrix-supported diamicton with an abundance of bedrock clasts. Stones and boulders are subrounded. Occasionally, the clasts are in contact with each other. A 15 cm large clast of a locally known clayey till was found within this unit. A clast fabric analysis revealed no preferred orientation of the clasts (Figure B-7c).

Pollen analysis: Samples were taken in the fine-grained sediment in the fractures as well as in the fine-grained lenses in the diamicton for pollen analysis (Appendix C; /Robertsson, 2004/). All samples show large similarity although the pollen content is relatively low. The composition suggests interglacial conditions, but the position of the sediment (within fractures and till) as well as the occurrence of pre-Quaternary (Paleozoic) palynomorphs clearly indicates that the microfossils are not in situ. The results correspond well to analyses from other sediments in the area.

B6 Discussion and conclusion

The sediments at drill site 5 are interpreted as follows: Unit A is a deformation till, which has formed by the sedimentation of alternately debris flow, as well as sorted sand and silt in subglacial cavities. Subsequently, these sediments were subglacially deformed by the moving ice. The ice movement direction is difficult to determine, although extensive and time-consuming clast fabric analyses might have provided necessary statistical data. Unit B is interpreted as basal till. Although the strength of the clast fabric was poor, probably due to the coarse and partly clast-supported appearance of the sediment, it is likely that Unit B was deposited by an ice movement direction from the north. It is likely that both units were deposited during one and the same glaciation and that the inherited ice movement direction corresponds to the dominating striation on the rock surface. From evidence from this site, it is not possible to determine which temporal relationship the three sets of glacial striae have to each other.

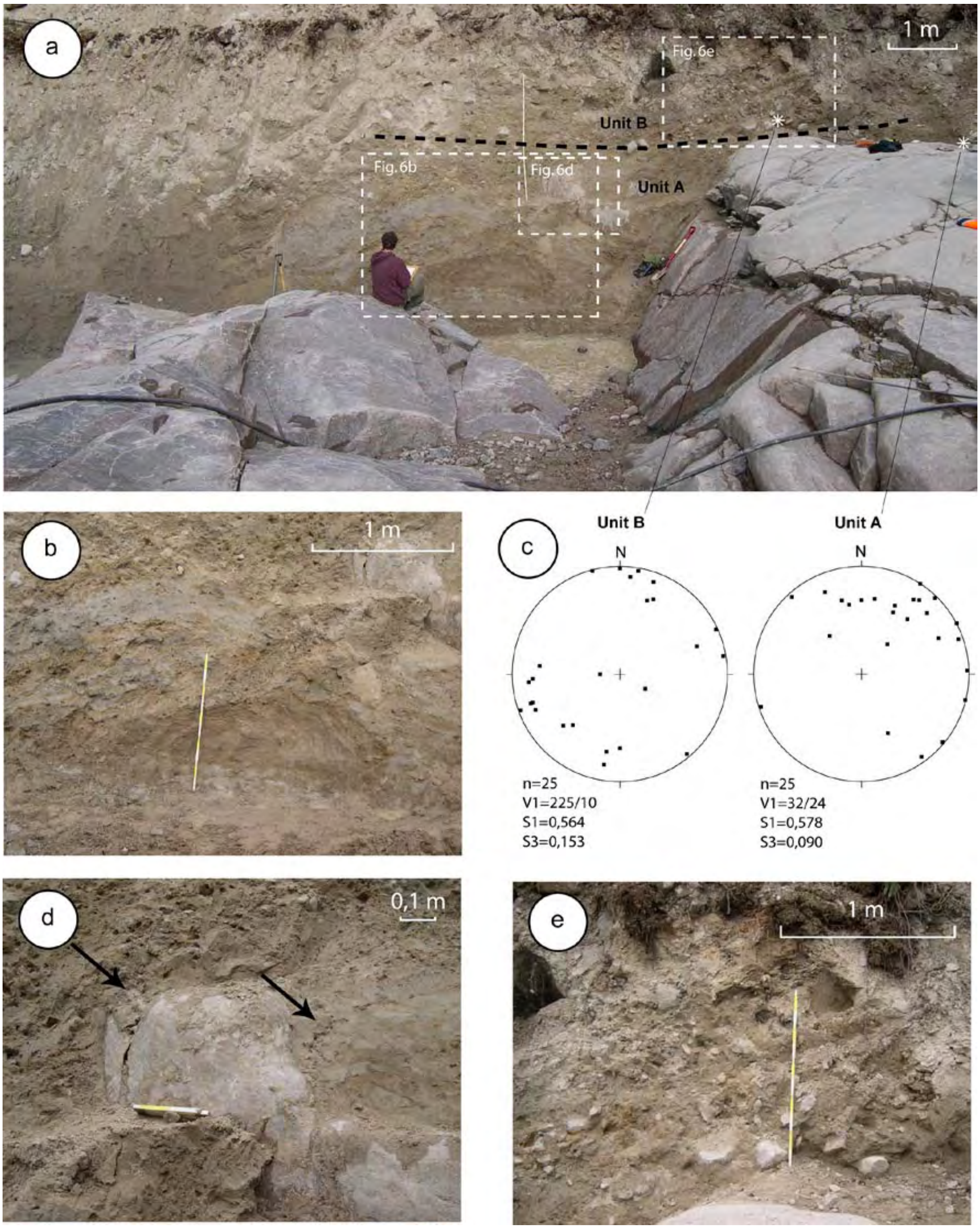


Figure B-7. *Till in the western wall. a) overview, sites for till fabric measurements are marked with *. b) sandy diamicton with inclusions of silt and sand, unit A. c) Schmitt stereographic plot (lower hemisphere) of till fabric measurements from unit A and B. V1=eigenvector orientation, S1/S3=eigenvalues. d) stringers of sand in connection to fractures in the bedrock. e) sandy till with stones, unit B.*

According to other investigations in this area /Sundh et al. 2004/, there are at least three ice movement directions: an oldest from the north, a younger from the northwest and a youngest from the north. It is probable that the ice movement direction from the north at drill site 5 represents the youngest direction in the area.

Fracturing and dislocation of the bedrock occurred during a period with glacial activity, although the process behind and the depth of this phenomenon are still unclear. The occurrence of fresh and unweathered fracture surfaces shows that at least some of the fractures are young and therefore cannot be related to older, i.e. pre-Quaternary, tectonic activity. The uplift and rotation of bedrock clasts indicate that the ice was active during or after the fracturing. The sediment found in open fractures is very similar to the fine-grained material in the deformation till and there are no indications that transport has occurred from the fractures outwards. The undeformed laminated sand and silt rather suggest an influx of sediment-bearing water into the fractures followed by a quiet sedimentation in open cavities.

The phenomenon of sediment-filled fractures in the bedrock can be regarded as exceptional but yet not unique. Similar features have been reported from the immediate vicinity /Stephansson and Ericsson, 1975; Carlsson, 1979/, from northern Uppland /Lokrantz, 2003/ and from Söderhamn (Sundh, pers. comm.). A detailed literature analysis on this topic could contribute to increase our knowledge about the cause and the dynamics of sediment-filled fractures.

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Microfossil analyses of samples from sediment filled fractures and till at drill site 5

Excerpt from:

Robertsson A-M, 2004. Microfossil analyses of till and sediment samples from Forsmark, northern Uppland. SKB P-04-110. Svensk Kärnbränslehantering AB.

April 2005

Abstract

As part of a study of microfossils (pollen and diatoms) at Forsmark, two samples from sediments in fracture fillings and three samples from silt in the overlying till at drill site 5 were retrieved and studied. One of the fracture sediment samples contained too few microfossils to allow quantitative analysis. The remaining four samples all contained pollen, while no diatoms were identified. The pollen spectra showed a rather uniform composition dominated by pollen of trees. This indicates an original deposition of the reworked pollen flora during an interglacial most probably the Eemian, c 120,000 years ago. A high frequency of Palaeozoic palynomorphs reflects erosion and incorporation of material from the Bothnian Sea where Palaeozoic bedrock is present.

Contents

C1 Introduction

Pollen and spores found in till beds have been eroded from organic deposits and incorporated by the inland ice. The pollen flora in these deposits originally reflects the composition of the vegetation in the area during the part of the ice free periods that preceded the stadial phases. Under favourable conditions, the rebedded pollen flora will show a typical interglacial (temperate) or interstadial (cool) “signature”. This can provide guidance when interpreting and dating minerogenic deposits such as different till beds and fine-grained non-organic sediments.

As part of a study of microfossils (pollen and diatoms) at Forsmark, a total of five samples were retrieved from drill site 5 and analysed. Table C-1 summarizes sample information. As can be seen in the table, two of the samples were taken from sediments found in open subhorizontal fractures, see Figure C-1, and three from silt in the till cover at the site. One of the fracture sediment samples contained too few pollen grains to allow quantitative analysis.

Table C-1. Samples collected at drill site 5 for analyses of microfossils. One of the samples contained too few pollen grains for analysis.

Sample no	Material	Comment
1	Silt in bedrock fracture	
2	Silt in bedrock fracture	Too few microfossils for quantitative analysis
3	Silt in till	
4	Silt in till	
5	Silt in till	

Figure C-1. *Sediment in bedrock fractures, as well as the till, was sampled at drill site 5.*

The study reported in this document was conducted in accordance with activity plan AP PF 400-03-98. No deviations from this controlling document were encountered. Data have been delivered to SKB's database SICADA, where they are available by the activity plan number.

C2 Method

Shortly, the microfossil analysis comprises the following sub-activities:

1. Samples are collected in the field.
2. Microfossils are extracted and slides are prepared in the laboratory.
3. The slides are analysed under a microscope at 400X or 1000X magnification and the microfossils are identified according to standard reference literature and counted.
4. The results are summarised and presented as absolute counts in a species list and in diagrams as percentage values of identified pollen (or diatoms).

Samples for pollen analysis (3–5 g) were prepared for analysis according to a sedimentation-separation method described by /Påsse, 1976/. This method is used for samples with a low organic content. Preparation for diatom analyses (5–10 g) followed a standard method /Battarbee, 1986/.

The slides for diatom analyses were scanned, but no diatom frustules were noted in either of the samples prepared.

Pollen was found in low frequencies, therefore 2–3 slides had to be analysed in order to reach a sum of at least 100 pollen grains. Some pollen grains were corroded and/or crumpled, which means that the group Varia (unidentified) constitutes 3–10% of all palynomorphs (microfossils with organic walls = pollen, spores, acritarchs) noted.

C3 Results

As mentioned, no diatom frustules were identified at a scanning of the slides. The diatoms have probably been dissolved and/or totally broken, and have not been preserved in the reworked fine-grained fraction of the till and sediments.

The results of the pollen analyses are presented as separate pollen spectra for each of the four samples in Figures C-2, C-3 and C-4. In Figure C-2 the total number of identified pollen of trees (AP = arboreal pollen), shrubs and herbs (NAP = non arboreal pollen) constitutes the basic sum, in Figure C-3 the number of tree pollen is used as the basic sum, and in Figure C-4 the total number of palynomorphs is used as the basic sum for calculation.

Tree pollen dominate the pollen spectra (88–91%), Figure C-2. There is a great similarity in the composition of the tree pollen spectra between sample 1 (fracture filling) and samples 3–5 (cover). *Betula, Alnus* and *Corylus* are most frequent, together constituting over 80% of the tree pollen. *Picea, QM* and *Carpinus* were noted with up to 5% each. This composition points to an originally interglacial pollen flora, in contrast to an interstadial signature with higher frequencies of shrubs and herbs. However, the composition of the vegetation during early Weichselian interstadials (Brörup, Odderade) in southern and central Sweden is so far very poorly known. In Denmark and northern Germany the forests included birch and pine mixed with some alder, spruce and larch during these interstadials /Behre, 1989/. The same forest composition may have been present in southern Norway, Sweden and Finland, but at the investigated sites the chronostratigraphy and the correlation of the supposed interstadial pollen floras are still uncertain /cf compilation by Donner, 1995/.

In reworked pollen spectra from earlier analysed till samples from central and northern Sweden a supposed interstadial composition includes mainly *Betula* among tree pollen together with only single pollen grains of *Pinus* and other trees /Robertsson et al. 2005/. Pollen of shrubs and herbs are frequent including e.g. *Betula nana*-type, Poaceae, Cyperaceae and *Artemisia*.

The samples contain approximately 14–28% pre-Quaternary palynomorphs, Figure C-4, which have been identified as Palaeozoic acritarchs, e.g. *Baltispheridium* spp and *Veryhachium* spp /cf Tschudy and Scott, 1969/. The presence of these pre-Quaternary microfossils indicates that material has been eroded and transported from the Bothnian Sea, where Palaeozoic bedrock is present /Norling, 1994/. The same kind of pre-Quaternary palynomorphs have earlier been identified at Skulla north of Uppsala, where a reworked clay was found embedded in till. According to the pollen and diatom flora this clay is suggested to be of Eemian age /Robertsson, 2000/.

In a study 30 years ago of fracture fillings found during excavation of a basin for cooling water at Forsmark, two pollen analyses were carried out on samples of silty sediments collected in the fractures /Stephansson and Ericsson, 1975/. A sample from the overlying till was analysed for comparison. The till sample was rare in pollen (basic sum 76), but tree pollen constituted 92% and herbs 8%. The dominance of tree pollen and that *Betula* was most frequent is in accordance with the spectra found in the present investigation. Other similarities are the low frequencies of *Picea* and *QM*. The study by Stephansson and Ericsson did not include pre-Quaternary palynomorphs.

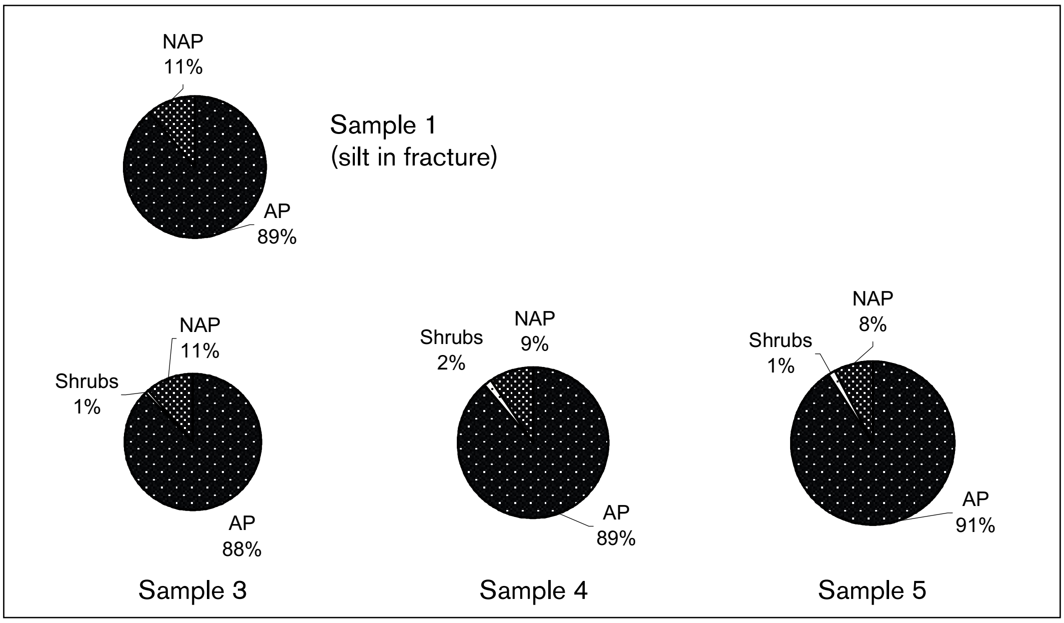

Figure C-2. *Total pollen spectra (trees, shrubs, herbs) in the analysed samples from drill site 5.*

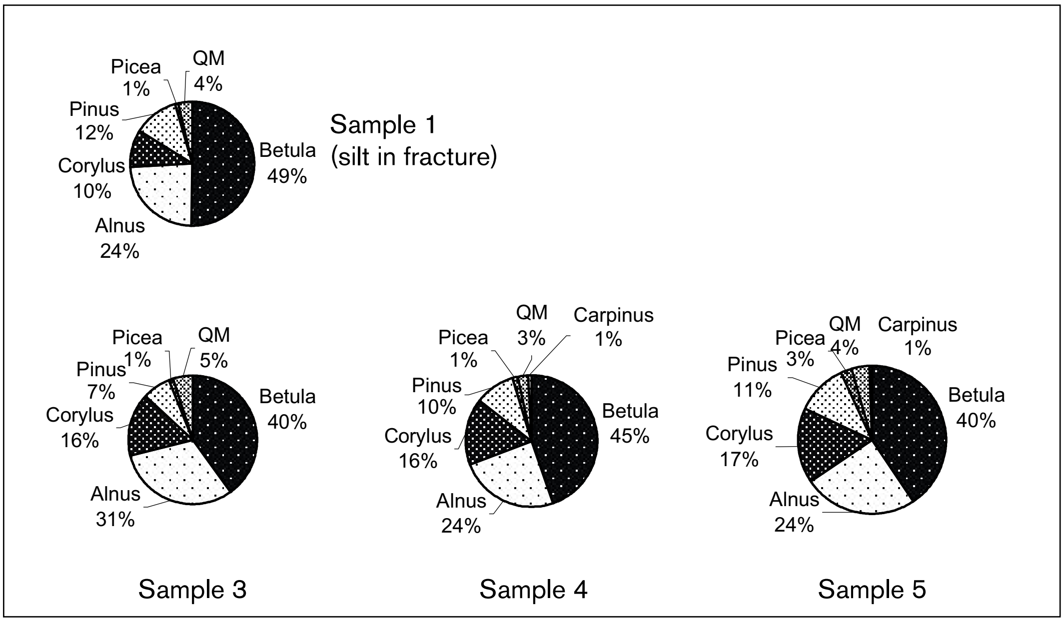

Figure C-3. *Composition of the tree pollen spectra (sum trees = 100%).*

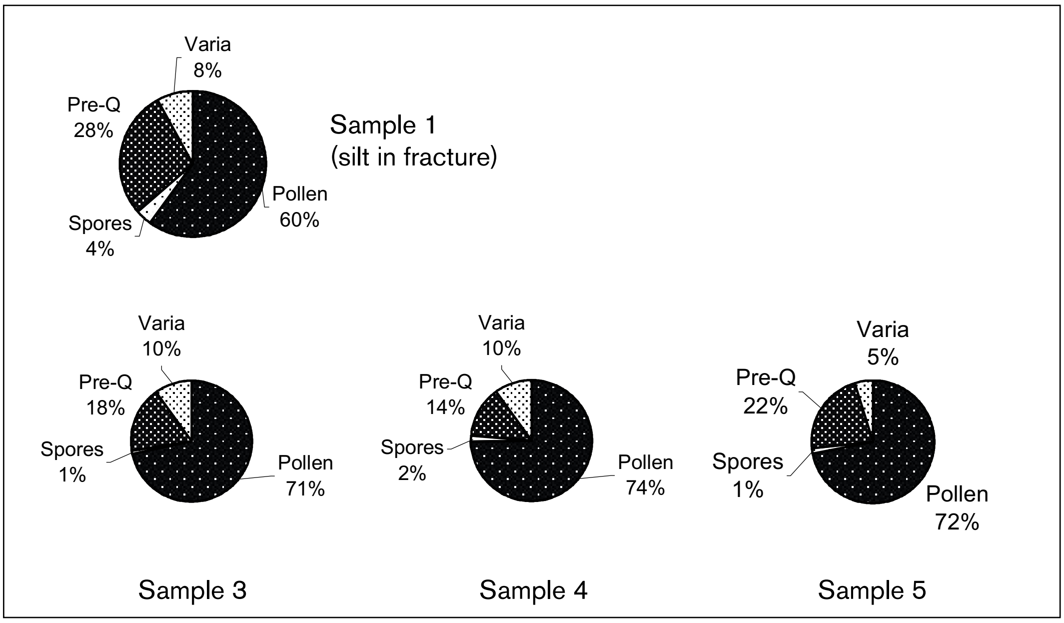

Figure C-4. *Total palynomorph composition including Varia (= corroded unidentified pollen).*

C4 Discussion

The composition of the reworked pollen flora shows an interglacial “signature” with a dominance of tree pollen including *Corylus, QM* and *Carpinus*. Those taxa were probably not growing in the area during the early Weichselian Brörup and Odderade interstadials. The most natural explanation is then that the interglacial deposits available for a glacier to erode would have been accumulated during the preceding (Eemian) interglacial, some 120,000 years ago. It should be stressed however, that our present knowledge about the vegetation history in Sweden and the presence of sediments from the Holsteinian interglacial (or still older ones) is so far very fragmentary /cf García Ambrosiani et al. 1998/.

Furthermore it seems reasonable to believe that sediments representing the later part of the interglacial were first removed by the ice and reworked. This is in agreement with the finding of pollen of *Picea* and *Carpinus*, which both spread during the later part of the Eemian interglacial /Behre, 1989/.

With respect to source material, the large contribution (approx 20%) of pre-Quaternary palynomorphs in the pollen flora suggests erosion and incorporation of fine-grained material from the Bothnian Sea with Paleozoic bedrock.

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Appendix D

Descriptions of thin sections and surface samples from near-surface fractures at drill site 5 – samples from short drill cores

Björn Sandström, Earth Sciences Centre, Göteborg University
Eva-Lena Tullborg, Terralogica AB, Gråbo

August 2004

Contents

D1 Introduction

In order to allow sampling of potential post glacial fractures documented at the site for the long cored borehole KFM05A at Forsmark (drill site 5), a number of short (7–12 cm) drill cores were drilled. Both vertical fractures and the probably more important horizontal fractures were sampled by the 10 short drillings (cf Figure D-1). This document presents results from microscopy (transmissive light) and SEM (Scanning Electron Microscopy) of three thin sections and two surface samples prepared from 5 of these near-surface fractures cut by the short drill cores. In addition, two analyses of stable O and C isotopes have been carried out on calcite from one of the vertical fractures visible in thin section.

The study reported in this document was conducted in accordance with activity plan AP PF 400-03-96. No deviations from this controlling document were encountered. Data have been delivered to SKB's database SICADA, where they are available by the activity plan number.

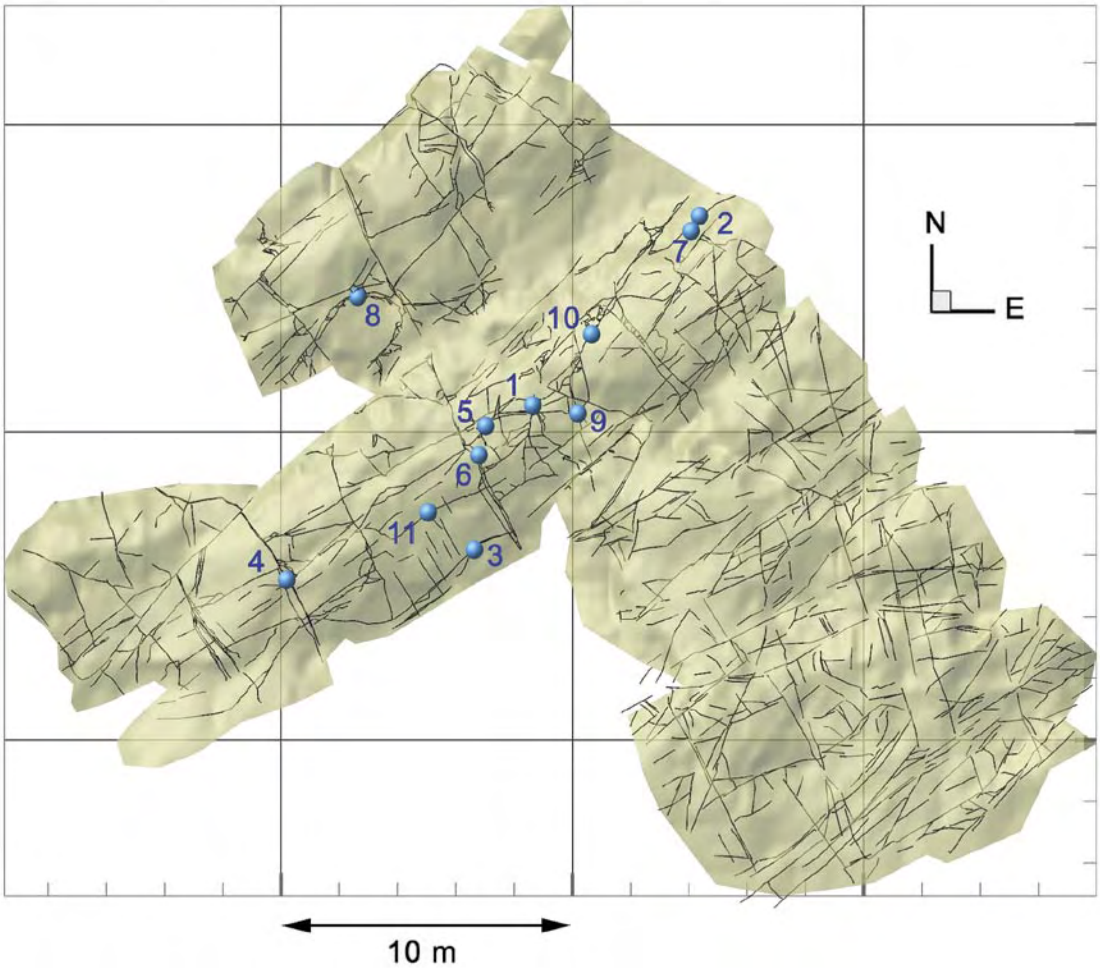


__Figure D-1.__ Map showing the outcrop exposed after excavation with the mapped fractures and the ten short drill holes marked with blue points. Drillcores 1 and 10 from subhorizontal fractures and 3, 4, and 6 from steeply dipping fractures have been sampled for this study.

D2 Objective and scope

The purpose of the study has been to examine the fractures in thin section and surface samples in order to describe the characteristics of eventual fracture minerals and potential additional minor fractures, and in addition, account for indications of the history of the fractures, if possible.

D3 Equipment

All the analyses were made at the Earth Sciences Centre at Göteborg University. The optical microscopic analyses and the photomicrographs were made with standard polarizing microscopes with digital photographic equipment. The thin sections were also analysed with scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). The fracture surface samples were examined with stereomicroscope and SEM-EDS. The SEM-EDS analyses of the calcite were carried out on an Oxford Instruments Link EDS mounted to a Zeiss DSM 940 SEM.

The O and C isotope analyses were made according to the following routines; Samples, around 200 µg each, were roasted in vacuum for 30 minutes at 400°C to remove possible organic material and moisture. Thereafter, the samples were analysed using a VG Prism Series II mass spectrometer with a VG Isocarb preparation system on line. In the preparation system each sample was reacted with 100% phosphoric acid at 90°C for 10 minutes, whereupon the released CO_2 gas was analysed in the mass spectrometer. All isotope results are reported as δ per mil relative to the Vienna Pee Dee Belemnite (VPDB) standard. The analysing system was calibrated to the PDB scale via NBS-19.

D4 Results

Thin section; drill core 3 – Shallow vertical fracture

No precipitated minerals were found on the fracture surface; the surface has a fresh unweathered appearance. Some minor microscopic fractures parallel to the fracture surface were identified. There are no indications of a more extensive saussuritization of the plagioclase toward the fracture in the wall rock.

Thin section; drill core 4 – Shallow vertical fracture

The fracture surface is coated with a thin layer of calcite (Figure D-2). The calcite is granular but shows no euhedral crystals. Crystallization under low-pressure conditions is suggested (e.g. prismatic structures are not identified). The calcite on the fracture surface contains 0.45% Mn. Calcite from this fracture has been analysed in respect of stable isotopes showing $\delta^{13}C$ values of –7.6 to –7.8‰ and $\delta^{18}O$ values of –9.3‰ PDB. These values are typical for potential recent, near surface calcite precipitated from meteoric water of $\delta^{18}O$ = –11 to –12‰ SMOW and at temperatures in the range of annual mean temperature at Forsmark in post-glacial time.

Two minor fractures are found in the thin section, both subparallel to the main fracture (Figure D-3). The SEM-EDS analyse shows that they also contain small amounts of calcite. There are no indications of a more extensive saussuritization of the plagioclase towards the fracture surface in the wall rock.

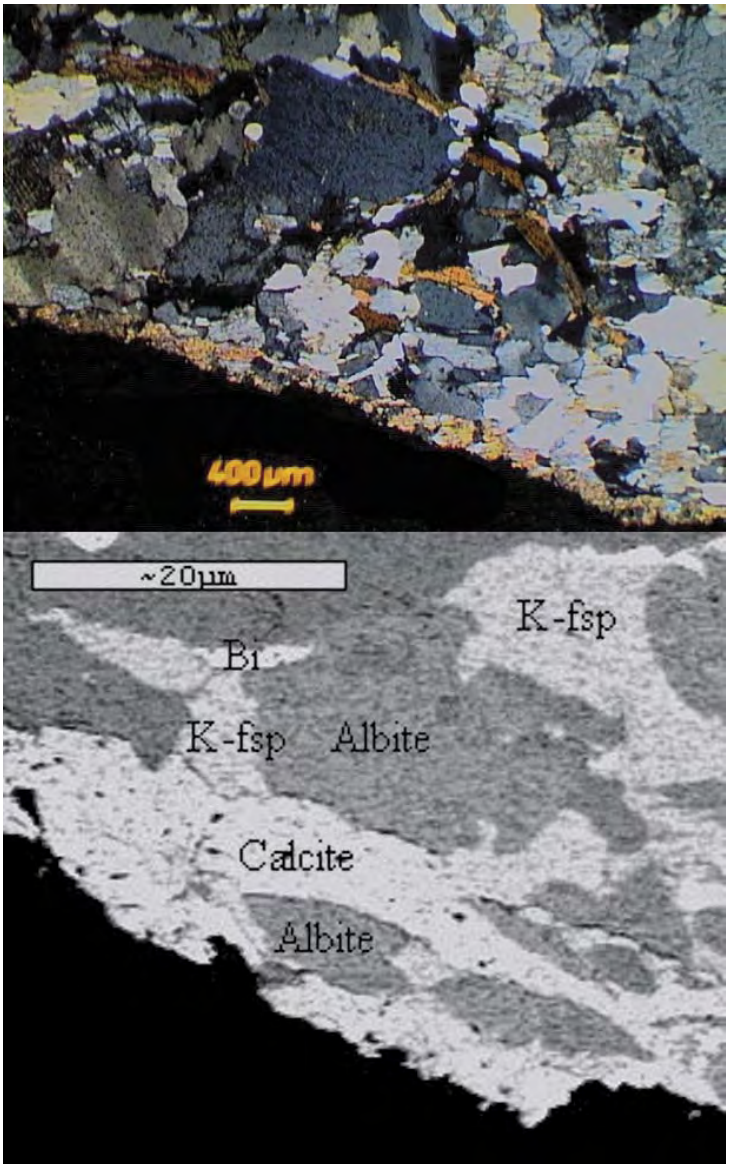


Figure D-2. *Fracture with thin calcite coating from drill core 4, photomicrograph with crossed polars (upper) and backscattered electron image (lower).*

Thin section; drill core 6 – Shallow vertical fracture

Calcite is found on the fracture surface, but only sporadically and where it appears, it is as very thin layers (Figure D-4). It is granular and shows no prismatic structure. As in thin sections 3 and 4, no indications of a more extensive saussuritization of the plagioclase towards the fracture surface can be seen in the wall rock.

Fracture surface; drill core 1 – Shallow horizontal fracture

The fracture surface contains small crystals of quartz. When viewed in the scanning electron microscope, the quartz crystals show euhedral crystals indicating that they have grown in an open fracture. No pronounced traces of weathering can be seen on the surface. The small irregular grains are not attached to the surface (Figure D-5).

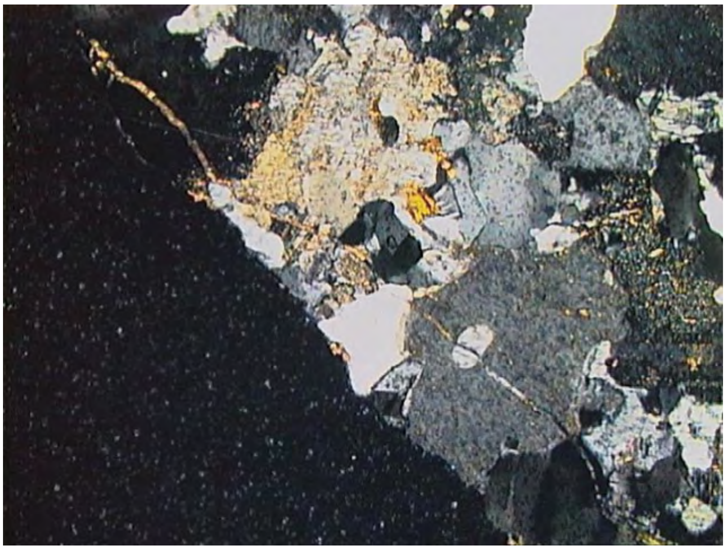


***Figure D-3**. Micro-fracture parallel to the main fracture, filled with calcite. (Photomicrograph with crossed polars, width of photo c 10 mm).*

Fracture surface; drill core 10 – Shallow horizontal fracture

The fracture surface is covered with small euhedral quartz crystals (Figure D-6), similar to the observations in drill core 1. The surface is fresh and shows no traces of weathering.

D5 Conclusions

A. There is no significant weathering on the fracture surfaces.

B. Two samples from horizontal fracture surfaces show occurrence of euhedral quartz crystals grown on the surfaces. This is typical for many fractures in the Forsmark area.

C. Calcite has been sampled from the vertical fracture coating in drill core 4. Stable isotope values are in accordance with recent precipitates (post-glacial) but could as well be older calcite precipitated during similar conditions.

This means that the horizontal fractures probably have older precursors (quartz is not expected to crystallise during ambient conditions), but some of the short vertical fractures could have been created in postglacial time.

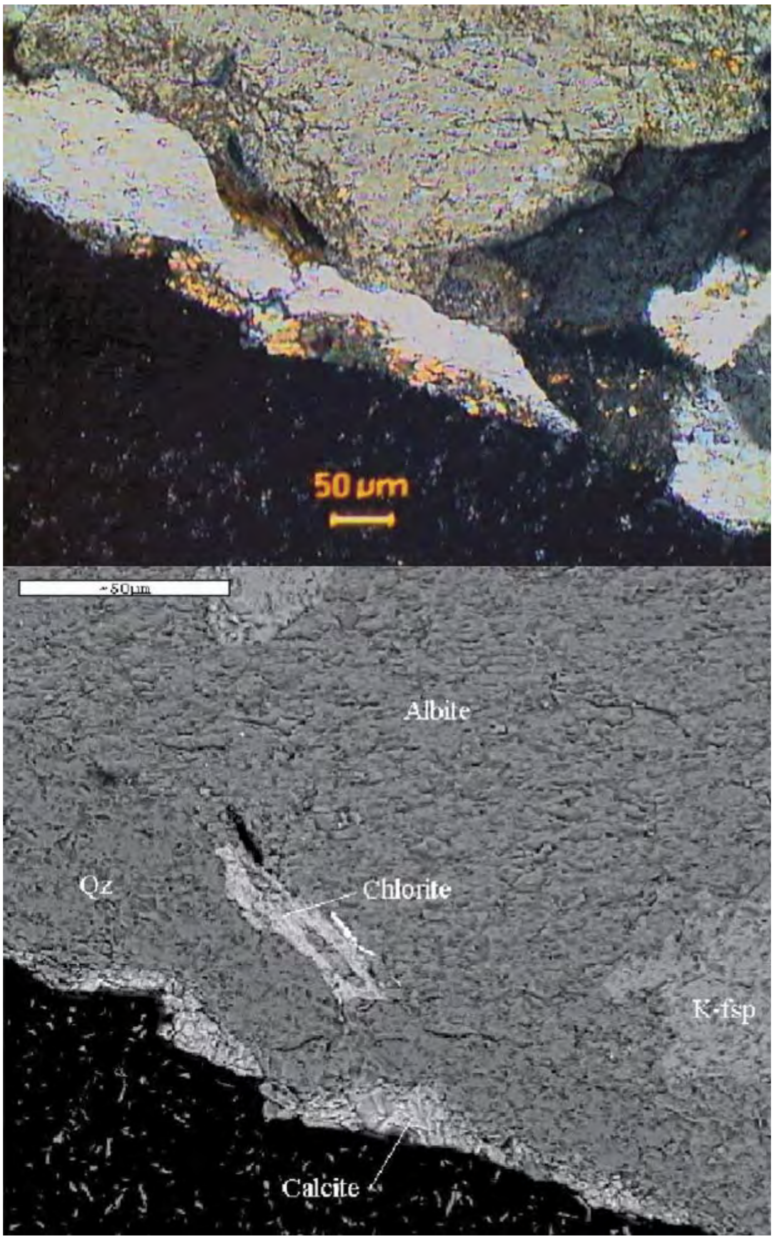


Figure D-4. *Fracture surface with a thin calcite coating from drill core 6, photomicrograph with crossed polars (upper) and backscattered electron image (lower).*

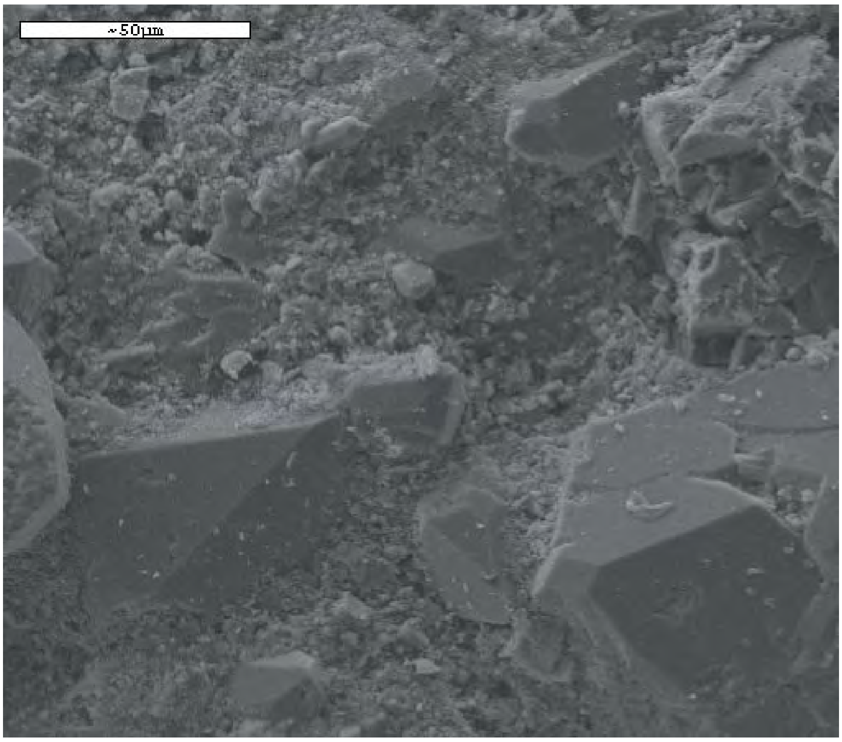


Figure D-5. *Electron image of quartz crystals on fracture surface from drill core 1.*

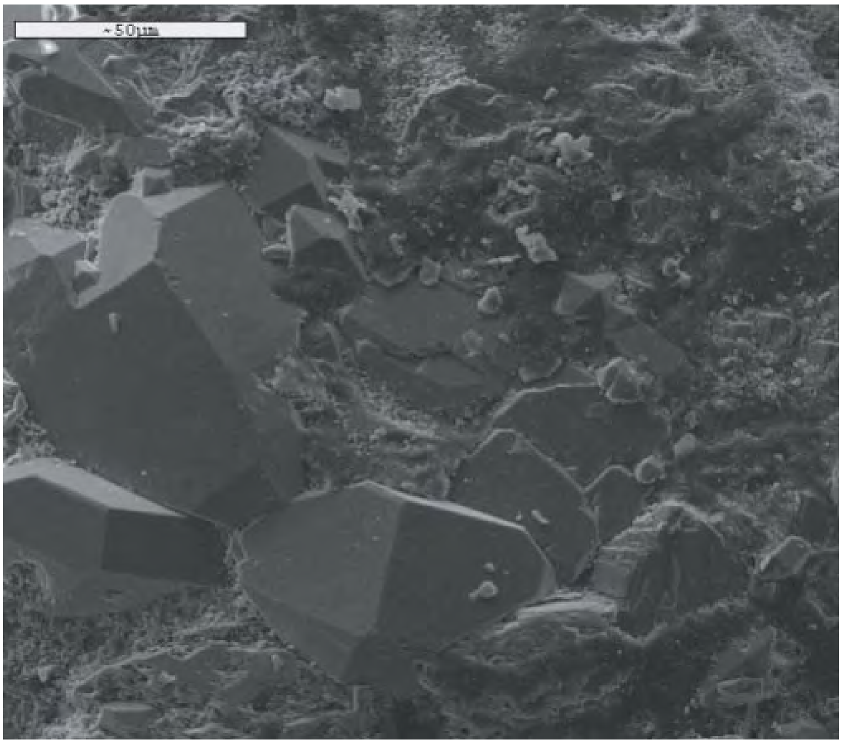


Figure D-6. *Electron image of euhedral quartz crystals on fracture surface from drill core 10.*

Appendix E

Ground penetrating radar measurements at drill site 5

Johan Nissen
Malå Geoscience AB

September 2005

Contents

E1 Introduction

Ground Penetrating Radar (GPR) measurements were performed at drill site 5 in October 2003. At that time, the soil cover at the site had been removed and detailed fracture mapping of the rock surface completed. The effort was made primarily because GPR can provide information from the shallow bedrock section (metres or at most about 10 m). The orientation and extension towards depth of the major, gently dipping fractures observed at surface was considered to be of special interest.

The GPR measurements were performed and interpreted by Malå Geoscience AB. First, a series of test measurements were done in order to assess the potential and optimize the type of radar antennas (frequencies) to be used. Then, a complete survey was conducted in a dense net of profiles, forming an area of c 20 by 10 m over the excavation. All measurements were made in walking speed. Due to the difficult topography, two operators were needed in order to keep the antenna "on the track".

The measurements reported in this document were conducted in accordance with activity plan AP PF 400-03-85 and method description MD 251.003 version 1.0. No deviations from these controlling documents were encountered. Data have been delivered to SKB's database SICADA, where they are available by the activity plan number.

E2 Equipment

Three different antennas, provided by Malå Geoscience were tested:

- 500 MHz shielded antenna.
- 250 MHz shielded antenna (see Figure E-1).
- 100 MHz shielded antenna.

All antennas were equipped with the RAMAC X3M control unit, and the RAMAC monitor XV11 was used for data collection.

***Figure E-1.** The RAMAC 250 MHz antenna. The antenna characteristics and the physical dimensions of this particular antenna showed up to be optimal for the present application (see Section E3).*

Due to the extreme topography within the measuring area, the measuring wheel normally used for logging the distance along the profiles was difficult to use. Instead, a Hip Chain measuring technique was applied. The Hip Chain utilizes a cotton string for distance measurements.

E3 Test measurements

In order to determine which antenna to be used for the survey, measurements were initially carried out with the three antennas available. In Figure E-2 is shown the results from one profile (Profile 18) measured with the three antenna frequencies. The resulting profiles are displayed without topographic corrections.

The following can be concluded from the test measurements (Figure E-2):

- All three frequencies show a good penetration depth, 8–12 m.
- Some features show up very clearly with all three antenna frequencies. One such example is an interpreted fracture zone denoted A in Figure E-2. In the 100 MHz diagram this zone shows up as one distinct reflector. In the 250 MHz and the 500 MHz diagrams the zone appears to be rather complex, with many small fractures.
- For mapping fractures the 500 MHz antenna frequency gives a too detailed picture.

Based on these and other test results, the optimum trade-off between resolution, penetration depth and signal strength was found to be 250 MHz. This was fortunate since the 250 MHz antenna showed to be the only antenna that was reasonably easy to handle on the very undulating exposed bedrock at the site. The 500 MHz antenna was simply too small to keep upright, and the 100 MHz antenna too large and heavy to move freely.

E4 Complete GPR 250 MHz survey

Based on the tests described in the previous section, it was decided to carry out the complete survey with the 250 MHz antenna only. Table E-1 shows the settings of the control unit for the data collection.

The profile location is shown in Figures E-3 and E-4.

The radar data were processed using the REFLEXW software package. The following filter steps were applied for all profiles:

- Removal of DC shift.
- Adjustment of zero time.
- Gain function (start time 27 ns, linear gain 27, exponential gain 0.33).
- Bandpass filtering (Butterworth 125 MHz to 500 MHz).
- Topography correction.

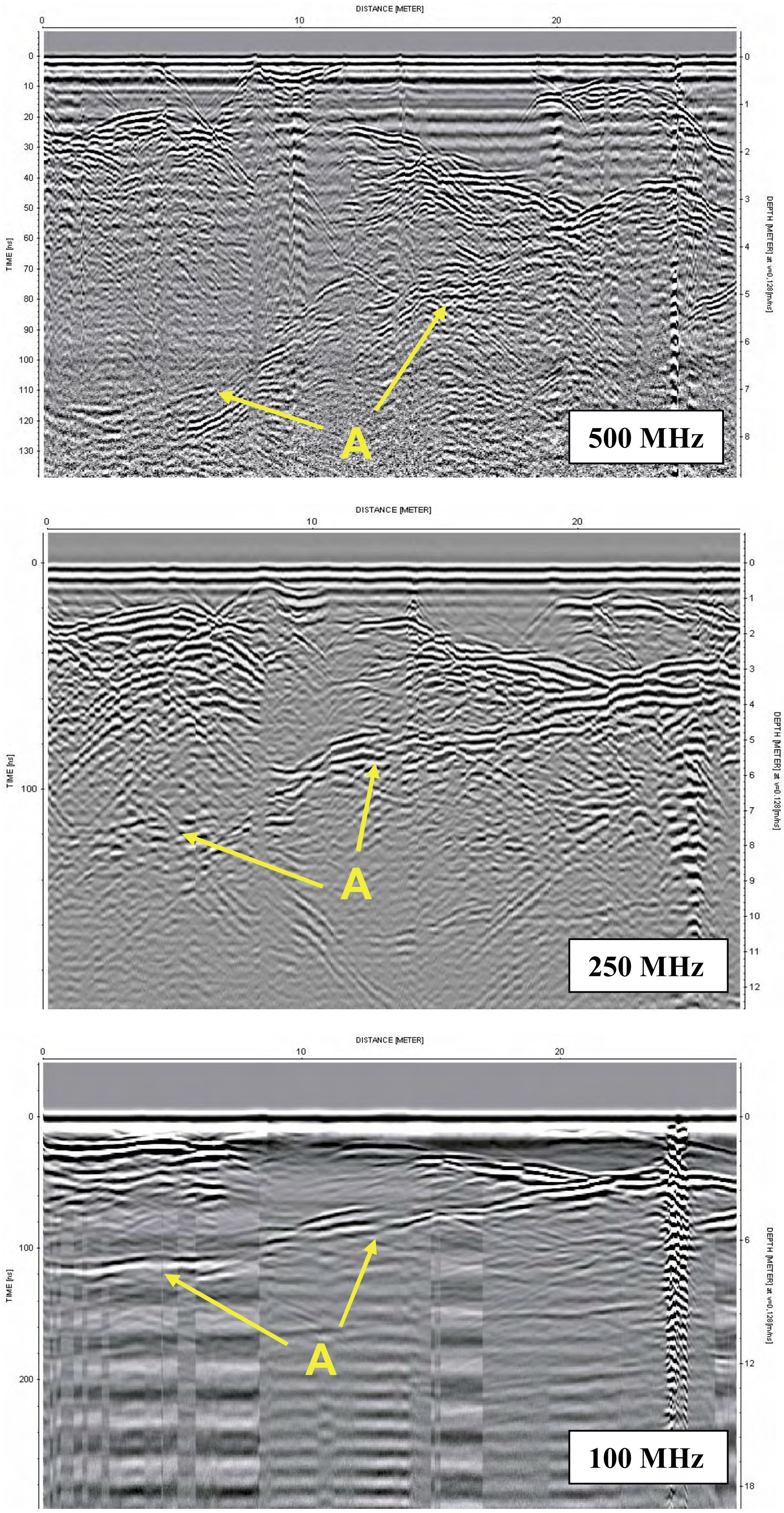


Figure E-2. *GPR measurements along Profile 18 with antenna frequencies 500, 250 and 100 MHz.*

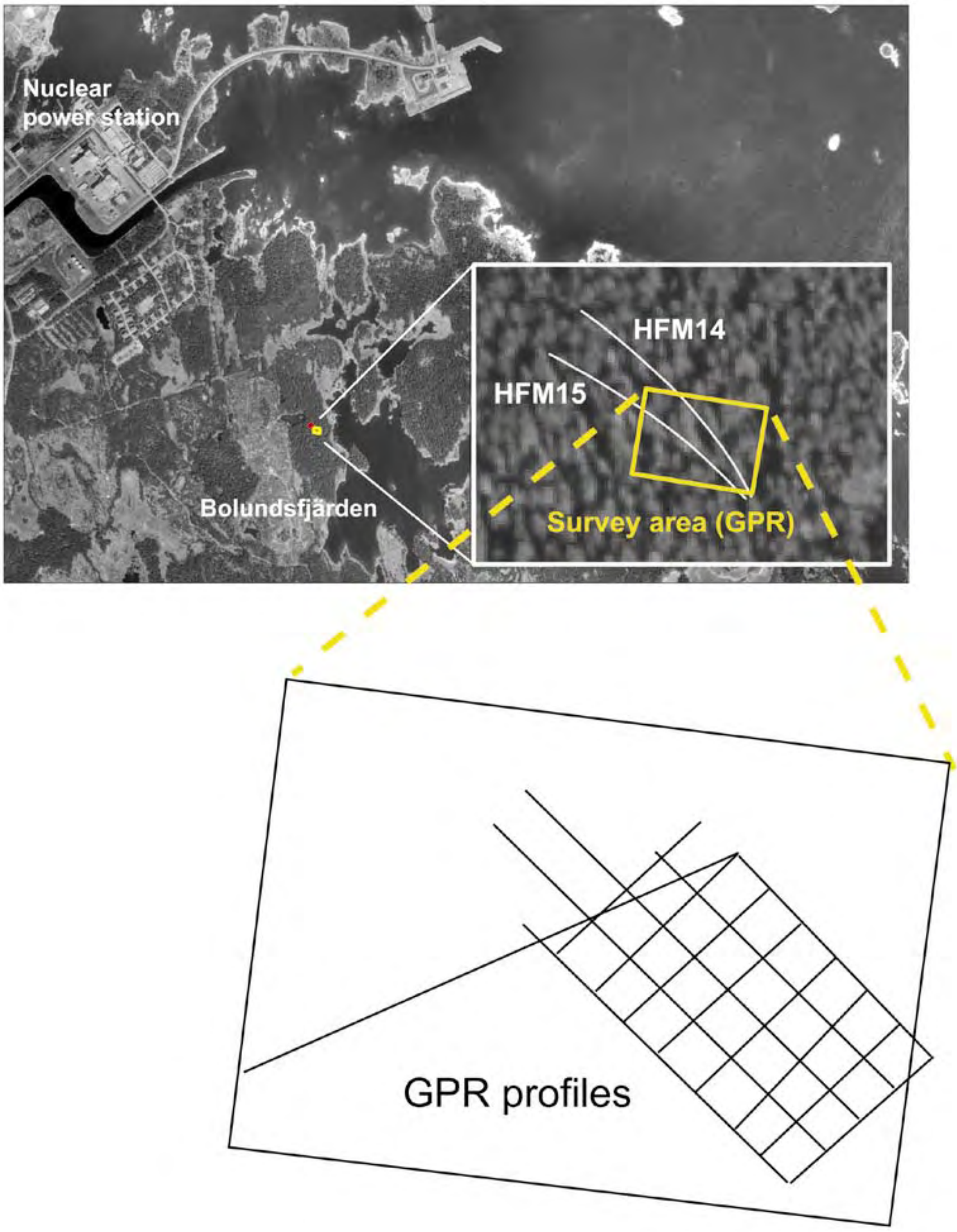


Figure E-3. Overview map showing the location if the GPR profiles at drill site 5.

Table E-1. Settings of the control unit for data collection with the 250 MHz antenna.

Number of samples	864
Sampling frequency	2560 MHz (10 times oversampling)
Trace interval	0.02 m
Antenna separation	0.36 m
Time window	337 ns
Number of stacks	4

In all processing and interpretation a velocity of 0.128 m/ns was used. This velocity was taken from estimates in nearby boreholes /1/. The topography was digitised from the map shown in Figure E-4.

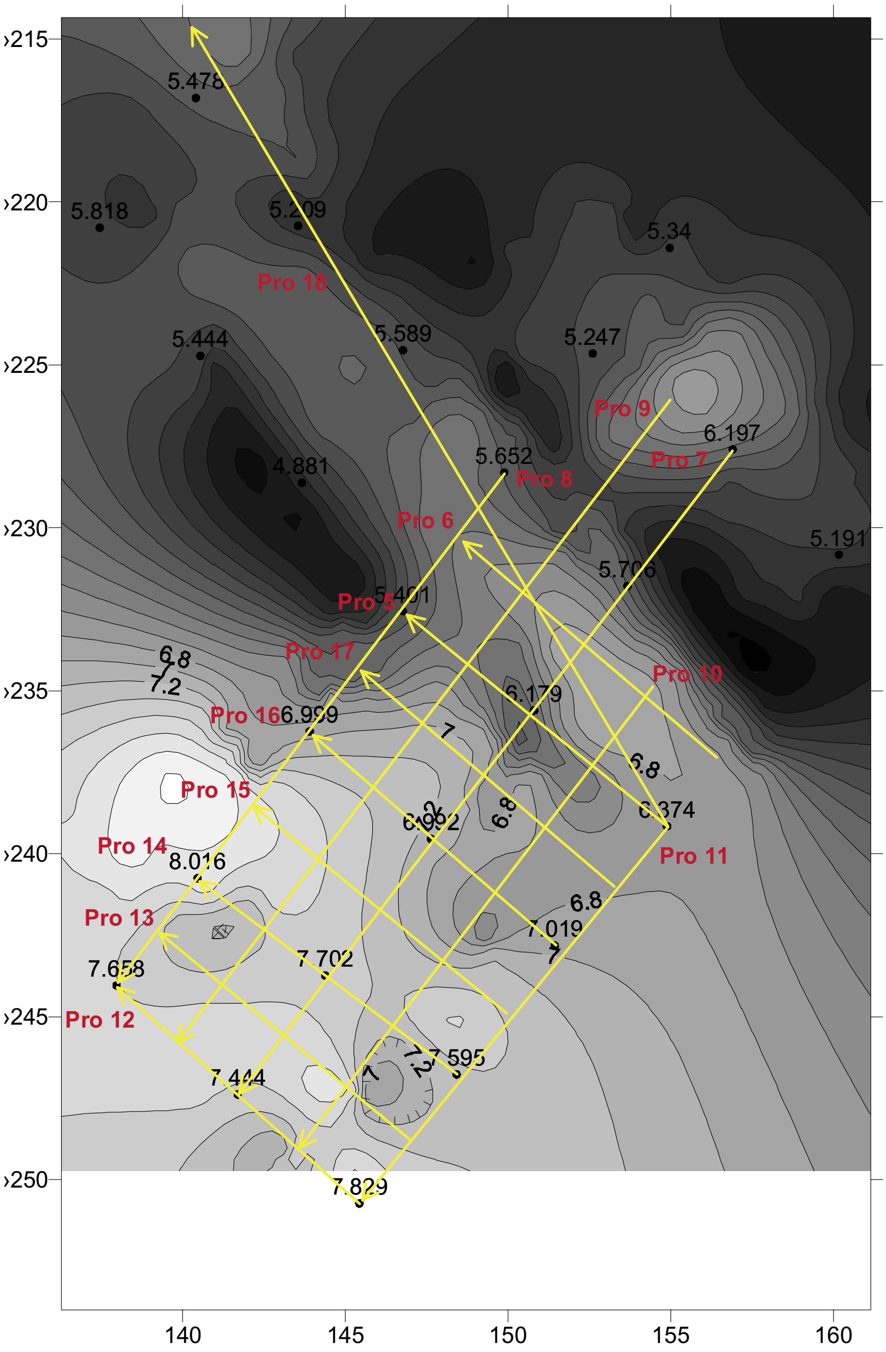


***Figure E-4**. Detailed topography and GPR profiles at drill site 5. Local co-ordinates.*

In order to quantify some of the major fractures, the radar sections were also interpreted using RADINTER. This program (initially developed for the interpretation of borehole surveys) is useful for picking fractures. However, due to the undulating surface topography the interpretation of dip angles with RADINTER is not very relevant, and the results are not documented here.

Figure E-5 shows one of the profiles (Profile 8) processed in REFLEX. The interpreted fracture zones are displayed in the radargram as well as in a separate plot. All profiles measured with the 250 MHz antenna show the same general behaviour, and are of equal quality. The processed data and interpretation are delivered to SKB.

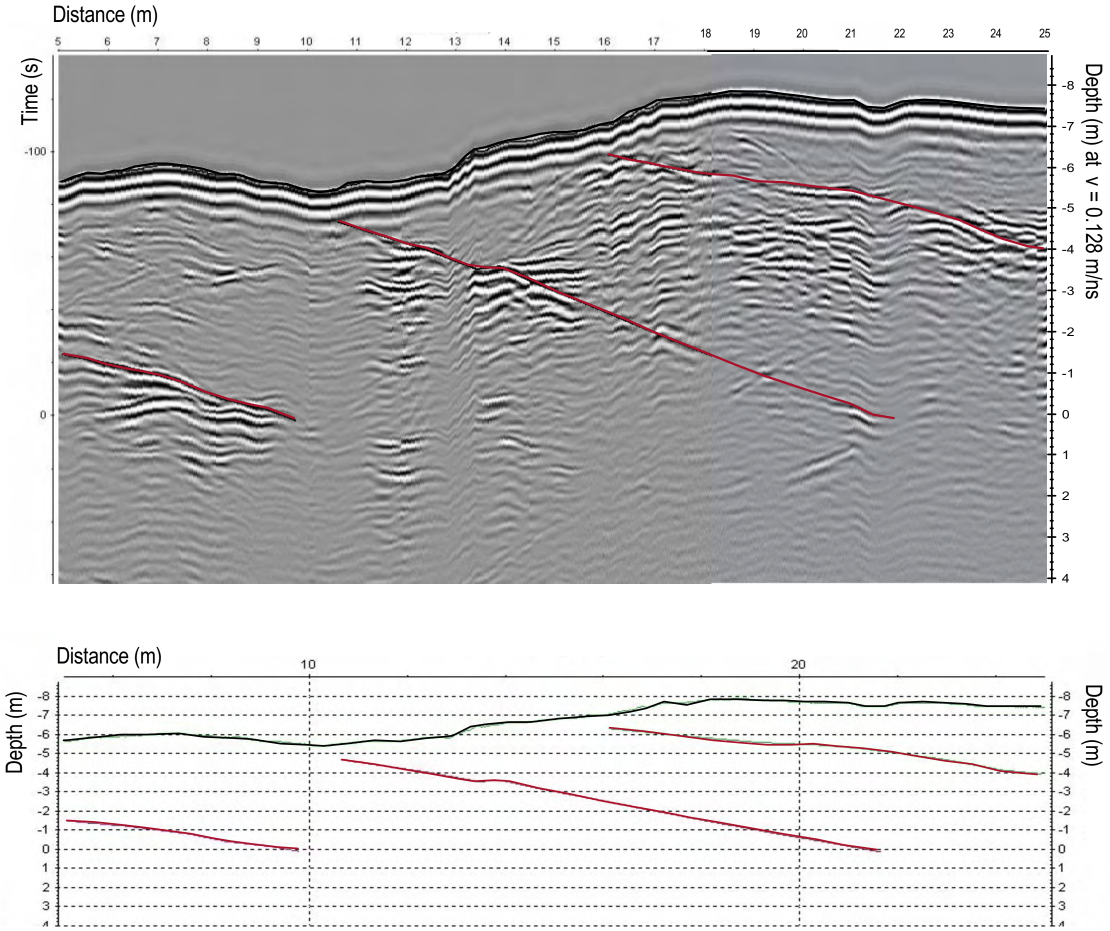


Figure E-5. Processing result and interpretation of GPR Profile 8.

E5 Data handling

The results from the radar measurements were delivered as raw data files on CD-ROMs to SKB. The raw data consist of two file types: *.rd3 containing the binary radar data and *.rad containing information about the settings etc in ASCII format.

The results after interpretation are delivered in pdf- and BMP formats. All radar interpretations (soil thickness and fracture zones) are furthermore delivered in ASCII files (*.pck).

E6 GPR results and surface observations

When comparing the GPR results with the surface mapping of major fractures, a remarkable agreement was observed. Three dominating, gently dipping fractures were mapped on surface and their extensions downwards could all be traced by the GPR. Figure E-6 shows the interpretation of GPR data and the fractures at the surface.

The integrated interpretation of all the GPR profiles exhibits the general picture demonstrated by Figure E-6. That is, superficial (within the GPR depth penetration), gently SE-wards dipping fractures.

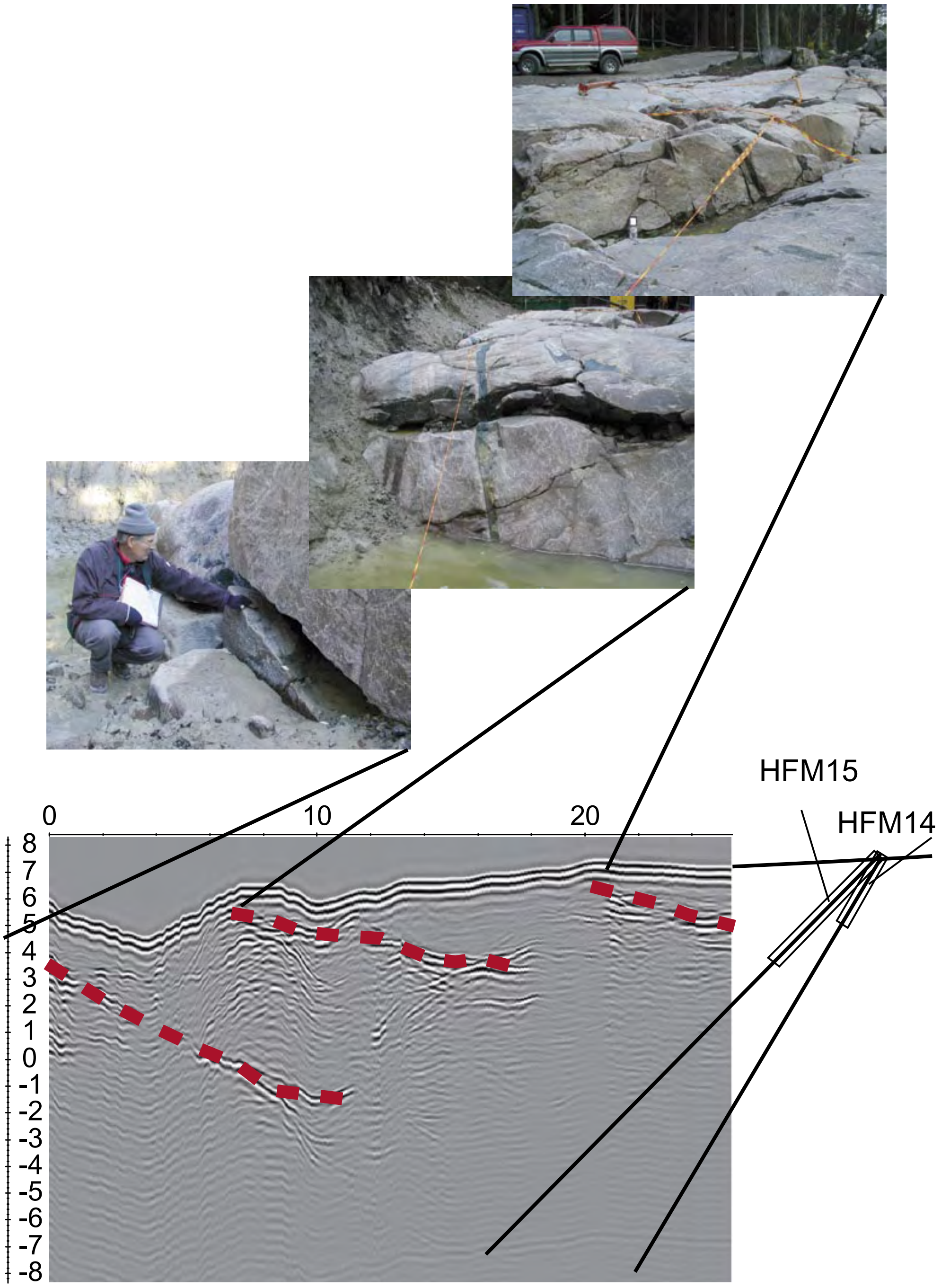


Figure E-6. *Three major fractures at drill site 5, as documented at surface and interpreted from the GPR measurements.*

The three predominant gently dipping reflectors most probably correspond to sheet joints. The maximum depths to which they can be clearly interpreted from the GPR-data is c 2 m, 3 m and 8 m respectively. However, the fractures might continue towards depth, undetected by the GPR survey due to the limited radar penetration. The possible continuations must therefore be investigated by means of e.g. percussion or core drilling.

References

/1/ Gustafsson C, Nilsson P, 2003. Geophysical Radar and BIPS logging in boreholes HFM01, HFM02, HFM03 and the percussion drilled part of KFM01A. SKB P-03-41. Svensk Kärnbränslehantering AB.

Appendix F

Boreholes HFM14 and HFM15 at drill site 5 – drilling, logging and interpretation

Lars-Åke Claesson, Mirab Mineral Resurser AB
Göran Nilsson, GNC AB

August 2005

Contents

F1 Introduction

Removal of the overburden at drill site 5 revealed unexpected conditions at the bedrock surface. This included a rugged topography, partly heavy fracturing, sediment fillings in several large-aperture fractures and associated dislocations of blocks. It was obvious from the surface observations that the anomalous conditions involved the uppermost few metres of bedrock. Assuming that they were caused by surface-related forces, an important question was whether they persisted to larger depths.

Data on rock conditions below the observable surface were required to resolve this question. Investigation methods for this purpose were restricted to surface geophysics and drilling. Both were employed at drill site 5. Ground penetrating radar was used to investigate the rock down to c 10 m (see Appendix E). Two percussion boreholes were drilled diagonally below the site, and further to vertical depths of c 130 m and 70 m respectively. An additional, vertical hole was drilled to 4.0 m depth.

This document summarizes the percussion drilling conducted at drill site 5 and selected results from subsequent logging and borehole testing. Borehole data are briefly discussed in terms of their contribution to the assessments of bedrock conditions at drill site 5. The drilling activities have been more completely documented by /Claesson and Nilsson, 2004/. Radar- and TV-logging has been reported by /Gustafsson and Gustafsson, 2004/, and other geophysical logging by /Nielsen and Ringgaard, 2004/. A geological interpretation of the boreholes, based primarily on BIPS-logging results supported by analysis of sampled drill cuttings, has been presented by /Nordman, 2004/. /Carlsten et al. 2004/ have conduced integrated geological single-hole interpretations. Finally, /Ludvigson et al. 2004/ have reported pumping tests and flow logging.

The drilling operations reported in this document were conducted in accordance with activity plans AP PF 400-03-68 and AP PF 400-03-82, and method description MD 610.003. Information on controlling documents pertinent to the various borehole logging- and interpretation efforts from which some results are also presented can be found in the references given above.

To enable performance of borehole measurements in HFM14 according to activity plan AP PF 400-03-68, a deviation was made. It appeared necessary to stabilize the borehole by a steel casing to 6.00 m to prevent fallouts from the borehole wall. In order to preserve the possibility to observe and investigate an open fracture encountered at approximately 3 m depth, a short additional percussion drilled borehole, denominated HFM14B, was drilled close to HFM14. Another nonconformity with activity plan AP PF 400-03-68 associated with the performance of HFM14 was that the borehole was drilled to full depth before its upper part was reamed and cased.

F2 Objectives and scope

As outlined above, the primary objective of the percussion drilling campaign was to investigate bedrock conditions, in particular fracturing, versus depth. Altogether three holes were drilled: Inclined boreholes HFM14, HFM15 and a complementary short hole denoted HFM14B. Figure F-1 shows locations on a site map and Figure F-2 shows in more detail the drilling geometry in relation to the excavation. HFM14 and HFM15 were both drilled from a location on the southeastern side of the excavation. This location was chosen because it allowed the rock beneath the outcrop to be penetrated by inclined boreholes and because access with drilling equipment was possible with a minimum of preparations and environmental impact.

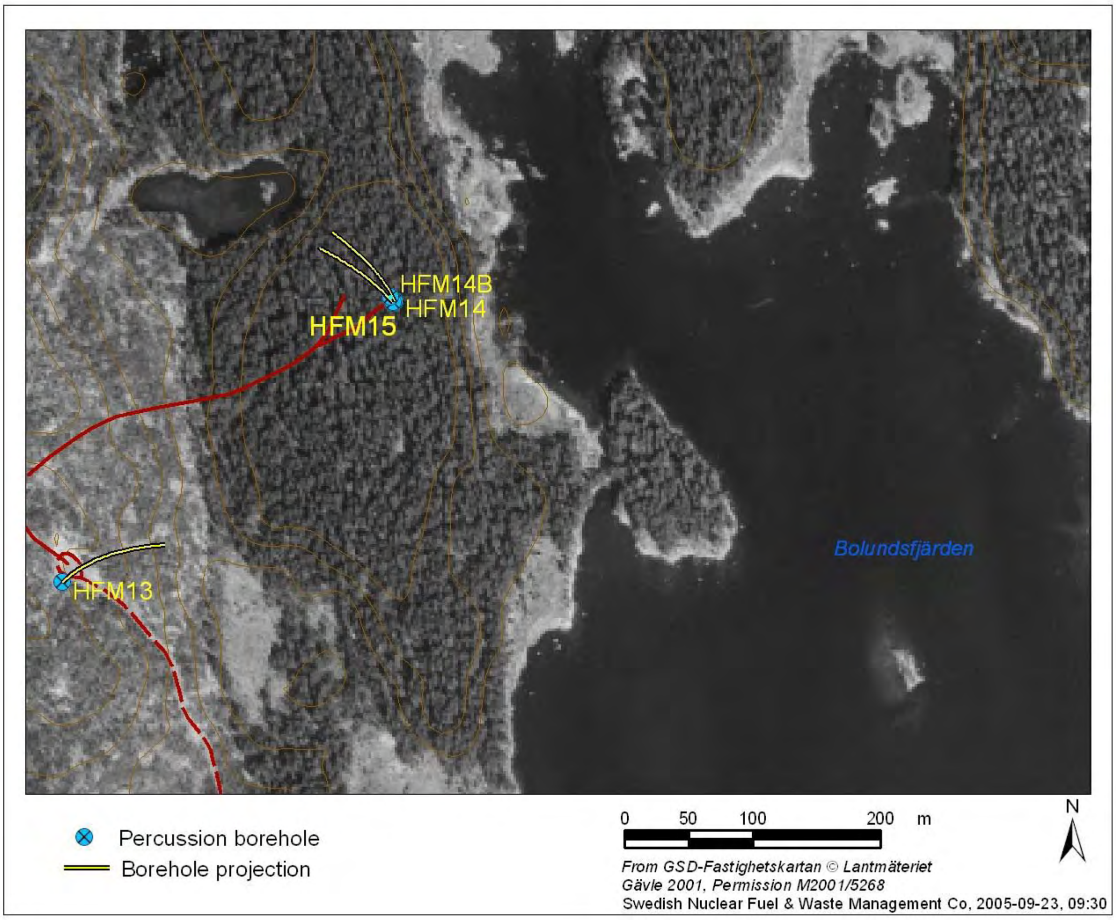


Figure F-1. *Locations and horizontal projections of percussion boreholes HFM14 and HFM15 at drill site 5.*

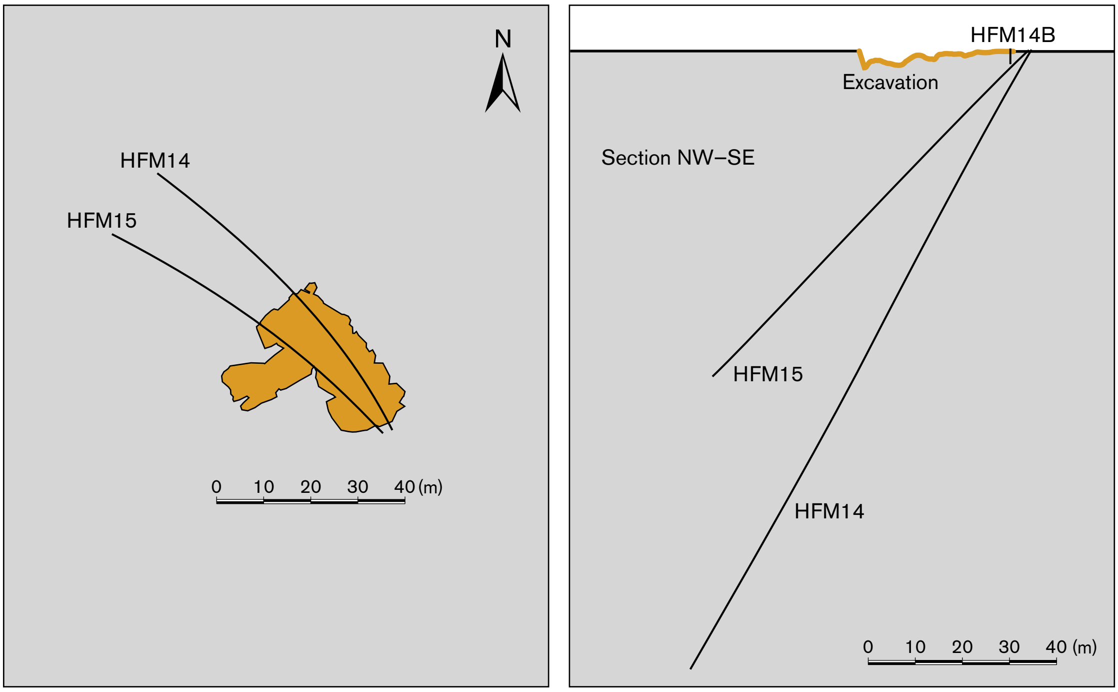


Figure F-2. *Percussion boreholes in relation to the geometry of the excavation at drill site 5.*

Geometrical data of the boreholes are summarized in Table F-1. Orientations where chosen with respect to the drilling objectives and experimental concerns such as access with cable-based logging devices. The reason for drilling two holes in slightly different orientations (17° in azimuth and 16° in inclination) was to provide some redundancy in data and hopefully permit cross-hole interpretations.

In addition to the main objective of investigating the rock mass, HFM15 was intended to serve as flushing water well for the subsequent deep core drilling at the site. This failed, however, due to a too limited water yielding capacity.

The vertical hole HFM14B was drilled to examine a major, open fracture at c 3 m depth. This fracture was noticed when drilling both HFM14 and HFM15, and documented by logging in HFM14. HFM14B was drilled to 4.0 m depth, and supplied with a casing reaching only a couple of decimetres below the ground surface.

Table F-1. Geometrical data for percussion boreholes at drill site 5.

	Borehole HFM14	Borehole HFM15	Borehole HFM14B
Collaring point coordinates (system RT90 2.5 gonV)	Northing 6699313.14 Easting 1631734.59 Elevation 3.91 masl	Northing 6699312.44 Easting 1631733.08 Elevation 3.88 masl	Northing 6699316.37 Easting 1631731.26 Elevation 3.91 masl
Bearing	331.75	314.31	32.97
Inclination (downwards)	59.81	43.70	89.00
Length	150.5 m	99.5 m	4.0 m
Casing length	6.0 m	6.0 m	< 0.5 m

F3 Drilling

F3.1 Equipment

The percussion drilling operations were performed in two campaigns during October–November 2003 by Sven Andersson in Uppsala AB, with support from SKB-personnel for measurements and tests during drilling.

Drilling was carried out with a Nemek 407 RE DTH percussion drilling machine (Figure F-3). Water and drill cuttings were discharged from the borehole with an AtlasCopco XRVS 455 Md 27 bars diesel compressor. The DTH drill hammer was of type Secoroc 5, operated by a Driconeq 76 mm pipe string. All DTH-equipment was cleaned with a Kärcher HDS 1195 high-capacity steam cleaner.

In order to prevent infiltration of surface water and shallow groundwater into deeper parts of the borehole, the normal procedure is to grout the gap between the borehole wall and the casing pipe with cement. No cement injections were however made in boreholes HFM14 and HFM15, because the increased fracturing of the bedrock entailed a high risk of filling the entire borehole with cement, which would make borehole measurements impossible.

Deviation measurements in HFM14 and HFM15 were performed with a Reflex EZ-shot (magnetic) equipment. Azimuth and dip were measured every third metre. The coordinates for the collaring point and the measured values from the EZ-shot instrument were used for calculating the coordinates for every measured point along the borehole.

Flow measurements during drilling were conducted using measuring vessels of different sizes and a stop watch. Measurements of drilling penetration rate were accomplished with a carpenter’s rule and a stop watch.

Figure F-3. *The Nemek 407 percussion drilling machine in operation at drill site 5. Water and drilling debris is discharged to the container to the left. The fractured bedrock is seen in the foreground.*

Samples of soil and drill cuttings were collected in sampling pots and groundwater in small bottles. A field measuring device, Kemotron 802, was used for measurements of electrical conductivity of the groundwater.

F3.2 HFM14

HFM14 was the first hole to be drilled at the site, and it was considered important to gain data also from the shallow section (less than about 10 m) that is usually permanently cased while drilling. This led to the choice of the technique known as Ejector NO-X for drilling through the overburden and shallow rock.

Figure F-4 shows the drilling sequence applied. The prefix "ejector" indicates that the discharge channels for the flushing medium, in this case compressed air, are constructed to reduce the exposure of the penetrated layers to the flushing medium, as compared to conventional systems. Thereby, contamination with oxygen and compressor oil carried by the compressed air (although in very small quantities), is limited.

The NO-X system involves a method for concentric drilling and casing driving through the overburden. A circular pilot bit, attached to a DTH-hammer shank, and with large internal flushing holes and external flushing grooves, is connected to a symmetrical ring bit (reamer). The pilot bit and the ring bit are both rotating clockwise, thereby drilling a borehole with a diameter large enough to let the casing easily slip down into the reamed borehole. The ring bit is rotating freely against the casing shoe, which is welded to the lower end of the casing. The casing is non-rotating during drilling.

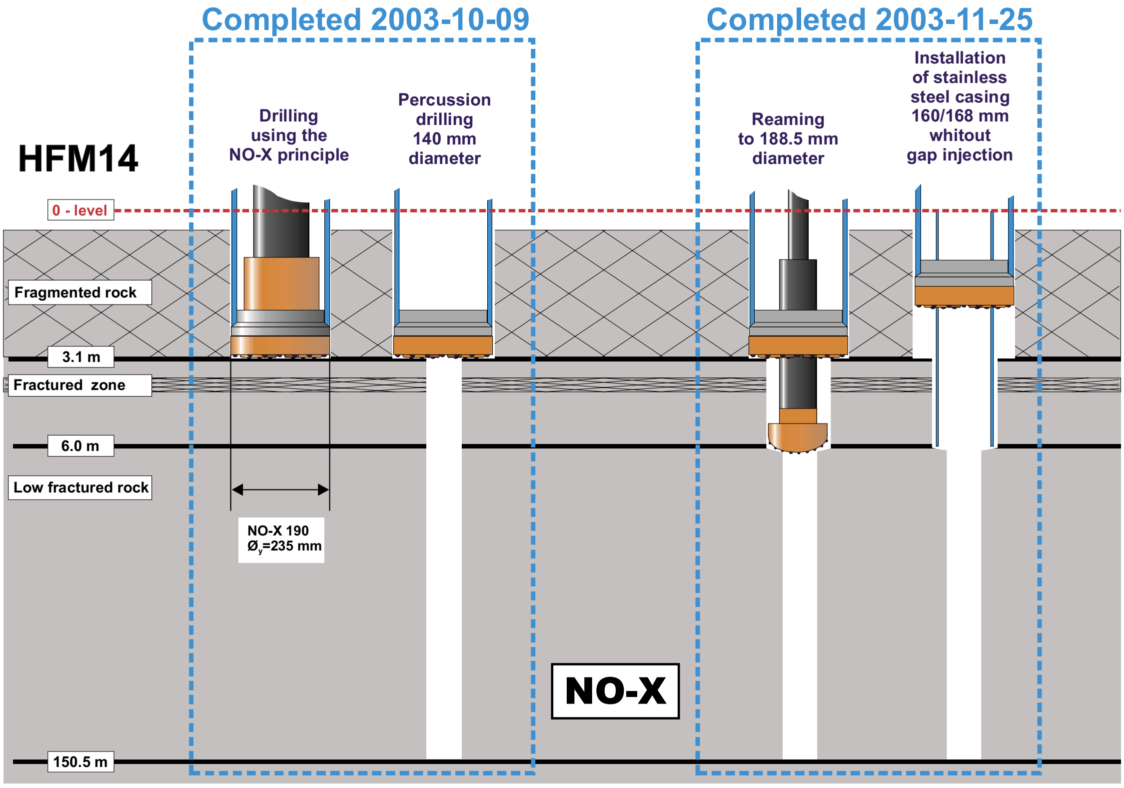


Figure F-4. Percussion drilling procedure for HFM14, according to the NO-X method. No cement grouting of the casing was performed.

Drilling through the overburden of borehole HFM14 basically followed the procedure for the Ejector-NO-X system, but in a somewhat unconventional manner. During drilling of a borehole with the diameter 235 mm, a temporary steel casing with an outer diameter of 219 mm was driven through the till overburden and through fragmented rock, into relatively fresh rock. The drilling pipes with the drill hammer and pilot bit were then retrieved from the borehole, after which drilling with c 140 mm commenced to full length.

Standard borehole logging was then performed. When preparing for long term monitoring after completed logging, difficulties were encountered in attempting to pass the major cavity at c 3.5 m with the monitoring equipment. To eliminate this problem, the hole was reamed to c 190 mm and cased down to 6 m length.

F3.3 HFM15

Gaining data from HFM14, it was considered important to drill the upper part of HFM15 with simultaneous casing driving in order to avoid hydraulic shortcut with HFM14 through the very large, open fracture observed at c 3 m length. Therefore, so called TUBEX technique (an ODEX-variant) was applied to drill through the overburden and 6 m into the bedrock.

The drilling sequence is illustrated in Figure F-5. The TUBEX method is based on a pilot bit and an eccentric reamer, which produces a borehole slightly larger than the external diameter of the casing. This enables the casing tube to follow the drill bit down the hole.

After the casing was set, drilling could continue and was now performed to the full borehole length with conventional percussion drilling, following the same procedure as for HFM14.

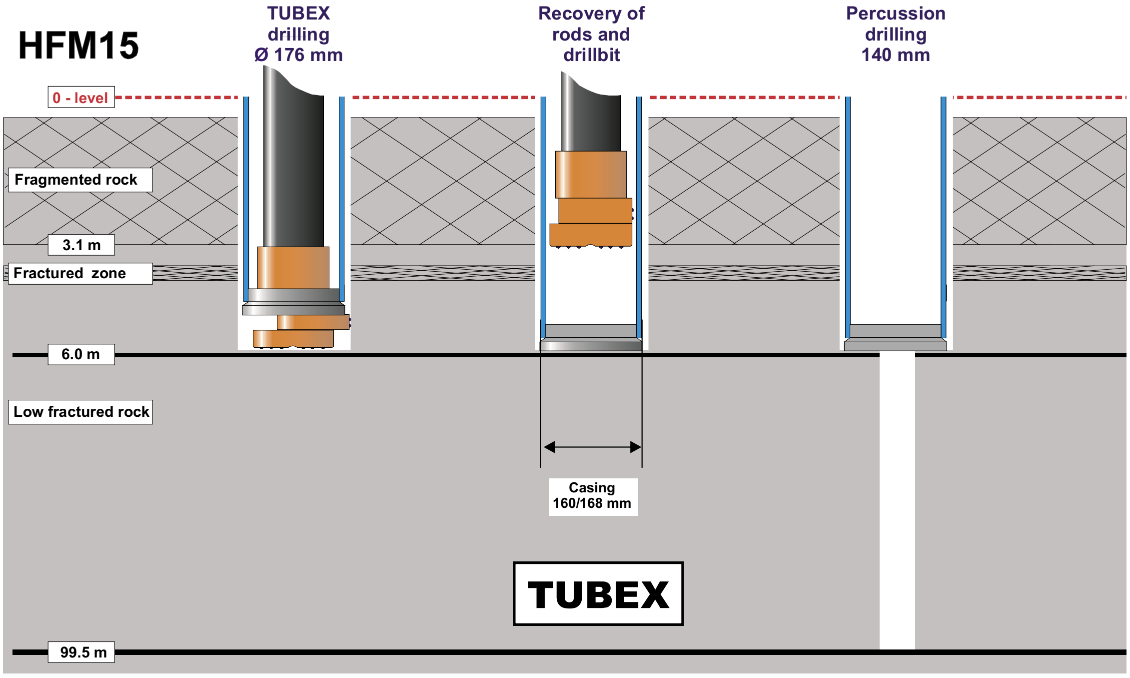


Figure F-5. *Percussion drilling procedure for HFM15, according to the TUBEX method. No injection was made.*

F3.4 Observations and sampling during drilling

During drilling of HFM14 and HFM15, a sampling and measurement program was performed, which included:

- Collecting one soil sample per metre drilling length. Analysis and results are reported by /Sohlenius and Rudmark, 2003/.
- Collecting one sample per 3 m drilling length of drill cuttings from the bedrock.
- Measuring penetration rate. The time needed for the drill bit to sink 20 cm was recorded manually in a paper record.
- Performing one observation of groundwater flow (if any) and water colour per 20 cm drilling length and a measurement of the flow rate at each major flow change observed.
- Measuring electrical conductivity (EC) of the groundwater (if any) at every 3 m drilling length (noted in a paper record).

Notable observations were made when drilling HFM14 at the length interval of approximately 3–3.5 m. Drilling parameters indicated very poor rock conditions within this interval. Flushing water carried large amounts of soil material after passage of this section. After some time, flushing water was discharged to the surface through nearby, open fractures. Figure F-6 illustrates this. The interpretation was that the drilling water eroded soil fillings from the superficial fractures, thus creating open hydraulic pathways to the surface.

Another observation, referring to a much larger scale, was hydraulic responses in boreholes at distance from the site. Figure F-7 shows results of hydraulic head monitoring in borehole HFM13, some 300 m southwest of drill site 5 (Figure F-1), during the period when HFM14 and HFM15 were drilled. It is seen that distinct and large hydraulic responses were recorded, which verifies hydraulic contact between the holes.

Figure F-6. *When drilling HFM14, flushing water was flowing in open fractures, from the borehole to surface.*

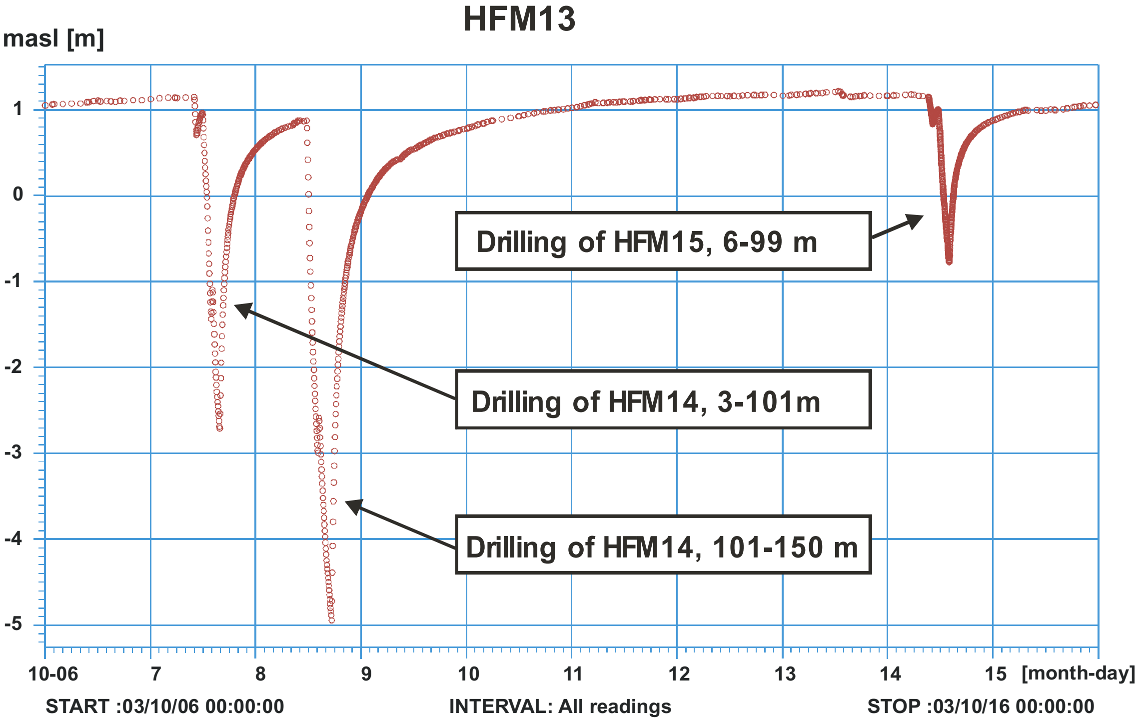


Figure F-7. *Hydraulic responses in HFM13 when drilling HFM14 and HFM15.*

F3.5 Finishing-off work

Finishing off work included rinsing of the boreholes from drill cuttings by a "blow out" with the compressor at maximum capacity during 30 minutes. The recovery of the groundwater table after rinsing was recorded, enabling a preliminary evaluation of hydraulic parameters. The drill pipes were then retrieved from the hole, and the diameter of the drill bit was measured. A deviation survey of the borehole completed the measurement programme during and immediately after drilling.

F4 Logging

Boreholes HFM14 and HFM15 were logged with borehole radar (RAMAC) and TV-camera (BIPS) shortly after drilling and later with standard geophysical logging. Pumping tests and flow logging have also been performed. Logging data have formed the basis for borehole mapping and, as a final activity, integrated single hole interpretation. Table F-2 summarizes the measurements and interpretations conducted, and associated references.

All logging- and interpretation work was done according to SKB standard procedures. Methods and procedures, as well as complete results, are fully documented in the references given, and other pertinent technical documentation. Results and interpretations of particular interest in the present context are summarized in the sections below.

Table F-2. Logging and interpretation of boreholes HFM14 and HFM15.

Activity	Reference
TV-camera (BIPS-logging)	/Gustafsson och Gustafsson, 2004/
Borehole radar (RAMAC-logging)	/Gustafsson och Gustafsson, 2004/
Conventional multi-method geophysical logging (resistivity, magnetic susceptibility, gamma density, sonic, acoustic televiewer)	/Nielsen och Ringgaard, 2004/
Mapping based on BIPS-images supported by analysis of drill cuttings (Boremap mapping)	/Nordman, 2004/
Pumping test and flow logging	/Ludvigson et al. 2004/
Integrated single hole interpretation	/Carlsten et al. 2004/

F4.1 HFM14

The most striking feature observed in the borehole was encountered within the section from 3 m and c 60 cm downwards. Here, the BIPS image indicated a wide, open fracture or void. This clearly correlates with the observations made during drilling. Below this more or less "empty" interval is a section with dense fracturing down to about 4 m. Data indicates a subhorizontal orientation of most of these features.

Figure F-8 shows the results of the integrated, single-hole interpretation of HFM14. The following comment is cited from /Carlsten et al. 2004/:

The borehole consists of one rock unit:

3–149 m RU1: Medium-grained metagranite-granodiorite with subordinate occurrences of pegmatitic granite, amphibolite, aplitic metagranite and one occurrence of fine- to medium-grained metagranitoid. Weak oxidation has affected the bedrock, more or less along the whole borehole length. In the upper 50 m, there are two crush zones and two fractures with apertures wider than 1 cm. These are also indicated in the radar measurements and as narrow geophysical anomalies. Uncertainty = 2.

Two possible deformation zones are indicated:

68–76 m DZ1: Increased frequency of open, flat-lying fractures, some with apertures wider than 1 cm. Mostly chlorite and unknown fracture filling minerals. Four radar reflectors with an intersection angle of 16–80° to the borehole axis. Low magnetic susceptibility and resistivity. Several caliper anomalies. Uncertainty = 3.

92–104 m DZ2: Slight increase of open, flat-lying fractures, with apertures less than 2 mm. Five crush zones (5–32 cm wide) in the lower half of the interval. Fracture filling minerals include quartz and chlorite. Four radar reflectors with an intersection angle of 50–63° to the borehole axis. Generally low magnetic susceptibility and resistivity. Several caliper anomalies. Uncertainty = 3.

F4.2 HFM15

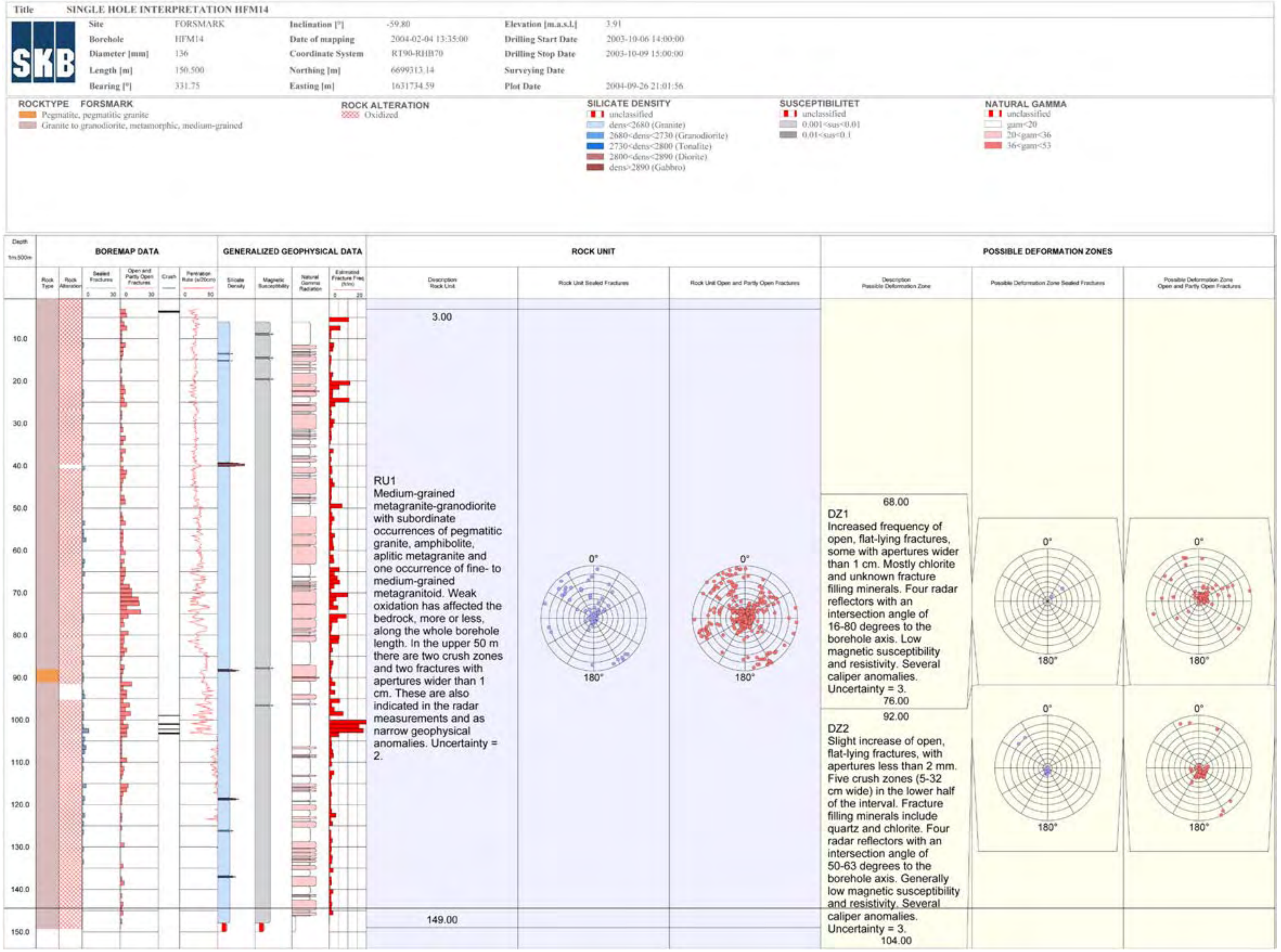
Figure F-9 shows the corresponding, single-hole interpretation result for borehole HFM15, commented as follows by /Carlsten et al. 2004/:

The borehole consists of one rock unit:

4–99 m RU1: Medium-grained metagranite-granodiorite with subordinate occurrences of pegmatitic granite and aplitic metagranite, predominantly in the lower half of the borehole, and four minor (< 2 dm wide) occurrences of amphibolite. Weak oxidation has affected the bedrock, more or less along the whole borehole length. Generally increased fracture frequency relative to the remaining part of the borehole, outside the possible deformation zone, in the length intervals 4–27.5 m and 63.5–75 m. These are also indicated in the radar measurements and as narrow geophysical anomalies. Two crush zones (14 and 60 cm wide) in the upper 11 m of the borehole. Uncertainty = 2.

There is one possible deformation zone in the borehole:

86–96 m DZ1: Increased frequency of open, flat-lying fractures, with apertures less than 2 mm. Mostly chlorite and unknown fracture filling minerals. Two radar reflectors with an intersection angle around 50° to the borehole axis. Low magnetic susceptibility and resistivity. Several caliper anomalies. Uncertainty = 3.



Title SINGLE HOLE INTERPRETATION HFM14

Site FORSMARK
Borehole HFM14
Diameter [mm] 136
Length [m] 150.500
Bearing [°] 331.75
Inclination [°] -59.80
Date of mapping 2004-02-04 13:35:00
Coordinate System RT90-RHB70
Northing [m] 6699313.14
Easting [m] 1631734.59
Elevation [m.a.s.l.] 3.91
Drilling Start Date 2003-10-06 14:00:00
Drilling Stop Date 2003-10-09 15:00:00
Surveying Date
Plot Date 2004-09-26 21:01:56

3.00

RU1
Medium-grained metagranite-granodiorite with subordinate occurrences of pegmatitic granite, amphibolite, aplitic metagranite and one occurrence of fine- to medium-grained metagranitoid. Weak oxidation has affected the bedrock, more or less, along the whole borehole length. In the upper 50 m there are two crush zones and two fractures with apertures wider than 1 cm. These are also indicated in the radar measurements and as narrow geophysical anomalies. Uncertainty = 2.

149.00

68.00

DZ1
Increased frequency of open, flat-lying fractures, some with apertures wider than 1 cm. Mostly chlorite and unknown fracture filling minerals. Four radar reflectors with an intersection angle of 16-80 degrees to the borehole axis. Low magnetic susceptibility and resistivity. Several caliper anomalies. Uncertainty = 3.

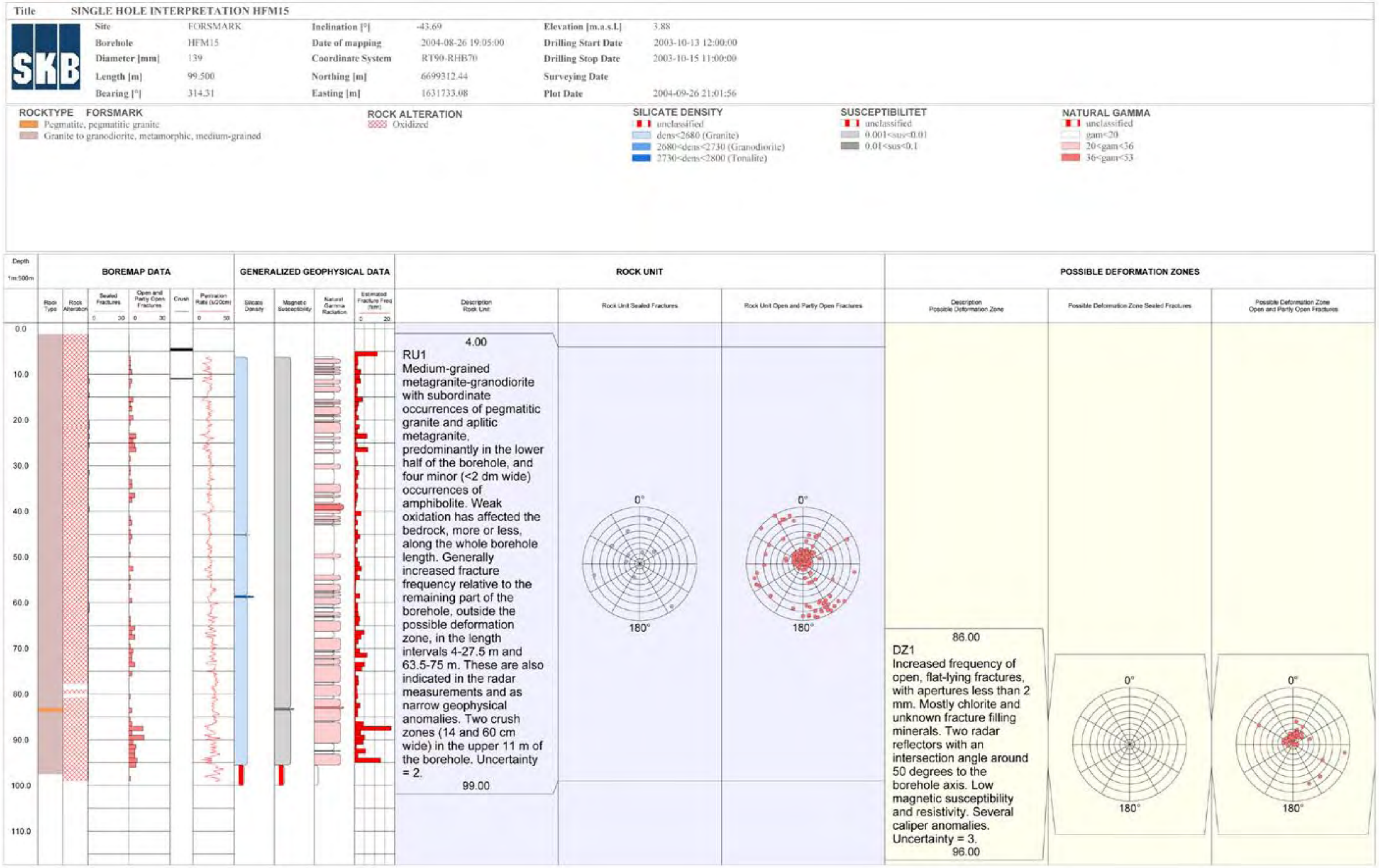
76.00

92.00

DZ2
Slight increase of open, flat-lying fractures, with apertures less than 2 mm. Five crush zones (5-32 cm wide) in the lower half of the interval. Fracture filling minerals include quartz and chlorite. Four radar reflectors with an intersection angle of 50-63 degrees to the borehole axis. Generally low magnetic susceptibility and resistivity. Several caliper anomalies. Uncertainty = 3.

104.00

Figure F-8. Geological single-hole interpretation for borehole HFM14 /from Carlsten et al. 2004/.



Title SINGLE HOLE INTERPRETATION HFM15

Site FORSMARK
Borehole HFM15
Diameter [mm] 139
Length [m] 99.500
Bearing [°] 314.31
Inclination [°] -43.69
Date of mapping 2004-08-26 19:05:00
Coordinate System RT90-RHB70
Northing [m] 6699312.44
Easting [m] 1631733.08
Elevation [m.a.s.l.] 3.88
Drilling Start Date 2003-10-13 12:00:00
Drilling Stop Date 2003-10-15 11:00:00
Surveying Date
Plot Date 2004-09-26 21:01:56

4.00
RU1
Medium-grained metagranite-granodiorite with subordinate occurrences of pegmatitic granite and aplitic metagranite, predominantly in the lower half of the borehole, and four minor (<2 dm wide) occurrences of amphibolite. Weak oxidation has affected the bedrock, more or less, along the whole borehole length. Generally increased fracture frequency relative to the remaining part of the borehole, outside the possible deformation zone, in the length intervals 4-27.5 m and 63.5-75 m. These are also indicated in the radar measurements and as narrow geophysical anomalies. Two crush zones (14 and 60 cm wide) in the upper 11 m of the borehole. Uncertainty = 2.
99.00

86.00
DZ1
Increased frequency of open, flat-lying fractures, with apertures less than 2 mm. Mostly chlorite and unknown fracture filling minerals. Two radar reflectors with an intersection angle around 50 degrees to the borehole axis. Low magnetic susceptibility and resistivity. Several caliper anomalies. Uncertainty = 3.
96.00

Figure F-9. *Geological single-hole interpretation for borehole HFM15 /from Carlsten et al. 2004/.*

It may be added that observations during drilling clearly indicated a crushed section at 4.3–4.9 m. Since the uppermost 6 m of the hole were cased while drilling, this section was not logged. Another, c 15 cm wide crushed zone was found at about 10.9 m.

HFM15 was also subject to hydraulic testing. Figure F-10 shows a result from this work. The diagram illustrates calculated, cumulative transmissivity along the hole. Below c 89 m, the borehole transmissivity falls below the measurement limit. As can be seen, transmissivity changes are found in four sections indicating one or more conductive structures within each section.

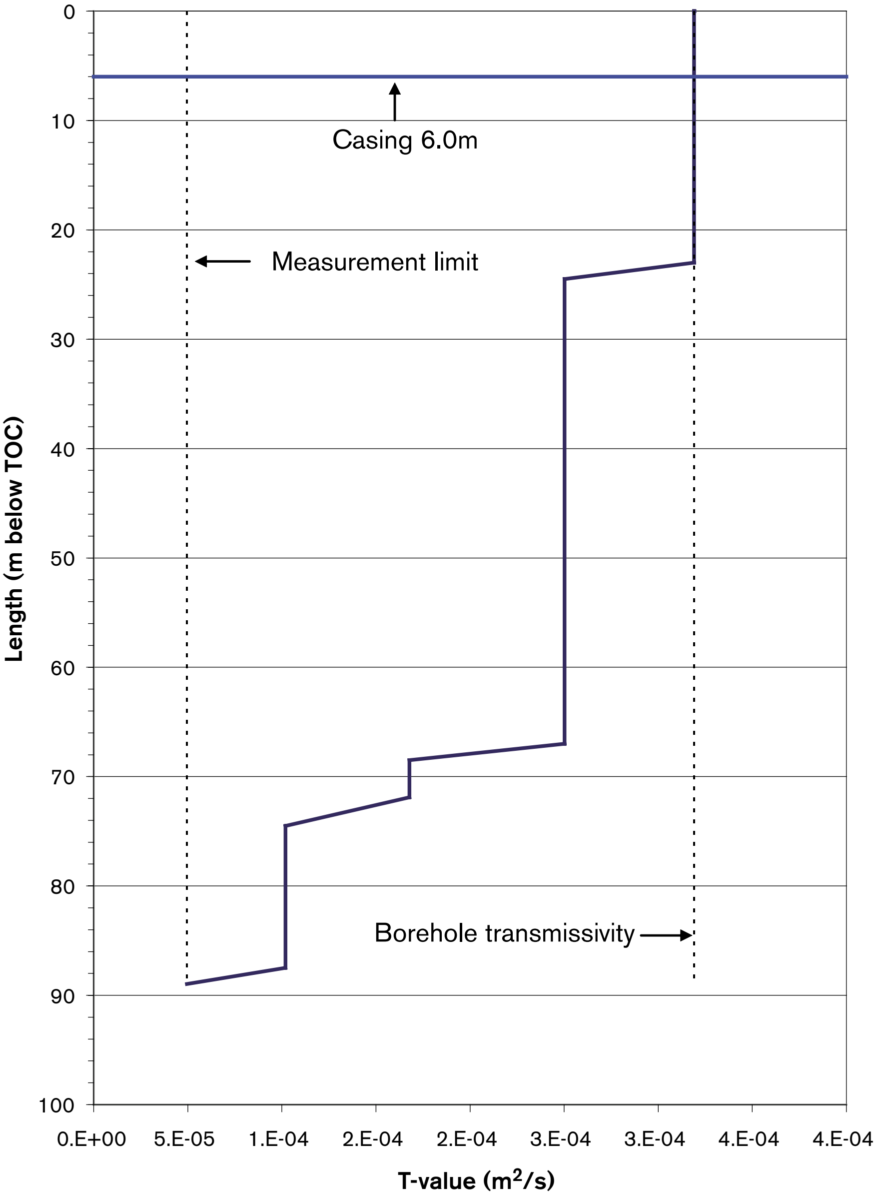


Figure F-10. *Calculated, cumulative transmissivity along the flow-logged part of borehole HFM15 /from Ludvigson et al. 2004/.*

F4.3 HFM14B

During drilling of HFM14B the predicted wide fracture was verified by a lack of drilling resistance between 2.8 m and 3.2 m. When flushing the borehole soil material was washed out, leading to hydraulic contact to the ground surface. No logging was performed in this hole.

F5 Interpretation

Figure F-11 shows a vertical, NW-SE section of the uppermost 20 m at drill site 5. The boreholes are projected on the section neglecting the small differences in azimuth between the orientation of the section and the borehole bearings. Data on fracturing are indicated in generalized form.

Starting from surface, the most striking observation is the wide, open fracture or fracture zone intersected by all three boreholes at some 3 m depth. In summary, observations are (depth intervals given refer to approximate vertical depth from the local ground surface):

- HFM14, 2.5–3.0 m: Crush or open fracture, originally containing soil material, hydraulic connection to surface after flushing away soil material.
- HFM15, 2.9–3.4 m: Crushed zone or large fracture with filling material indicated during drilling
- HFM14B, 2.8–3.2 m: Open fracture indicated during drilling (drilling terminated at 4.0 m).

Three major, gently dipping structures inferred from the ground penetrating radar survey (and also verified by mapping at their surface intersections), here denoted GPR1, GPR2 and GPR3, are also reproduced in the figure. There is little doubt that the fracture observed in the boreholes is identical to GPR1. Thus, this fracture appears to extend more or less horizontally to the southeast, at least to a distance corresponding to the borehole intersections. It is also evident that the large aperture (decimetres) and soil filling of this structure persists to a depth of at least 3 m.

For the remainder of the depth interval displayed in Figure F-11, i.e. below the large fracture at c 3 m and down to 20 m, data indicates that fractures occur at low frequencies. Figure F-11 shows open/partly open fractures only, but as can be seen in Figures F-8 and F-9, the frequency of sealed fractures is much lower. Closer examination of the data reveals that a majority of the fractures are subhorizontal, although steeply dipping sets are also present. More importantly, there are no indications of anomalous fracture apertures or presence of soil material in any of the fractures (below the major feature at 3 m). This has important implications with respect to the interpretation of data from surface mapping and GPR-surveying. GPR-records allowed the fractures GPR2 and GPR3 to be traced from surface and some 10 m into the bedrock. Extrapolating positions and orientations from the GPR-results yields that these two fractures would intersect HFM14 and HFM15 at c 6 m and c 15 m vertical depth respectively. Whether some of the fractures observed at these depths in the holes do in fact represent the continuation of GPR2 and GPR3 can not be determined. A 10 cm wide, crushed zone observed at about 7 m in HFM15 is a possible candidate. What can be stated, however, is that neither fracture apertures comparable to those seen at surface, nor any sign of soil infillings, can be found in the boreholes at these depths. It is therefore concluded that the uplifting- and sediment filling processes are, at least in these two cases, phenomena that involves only the superficial rock mass.

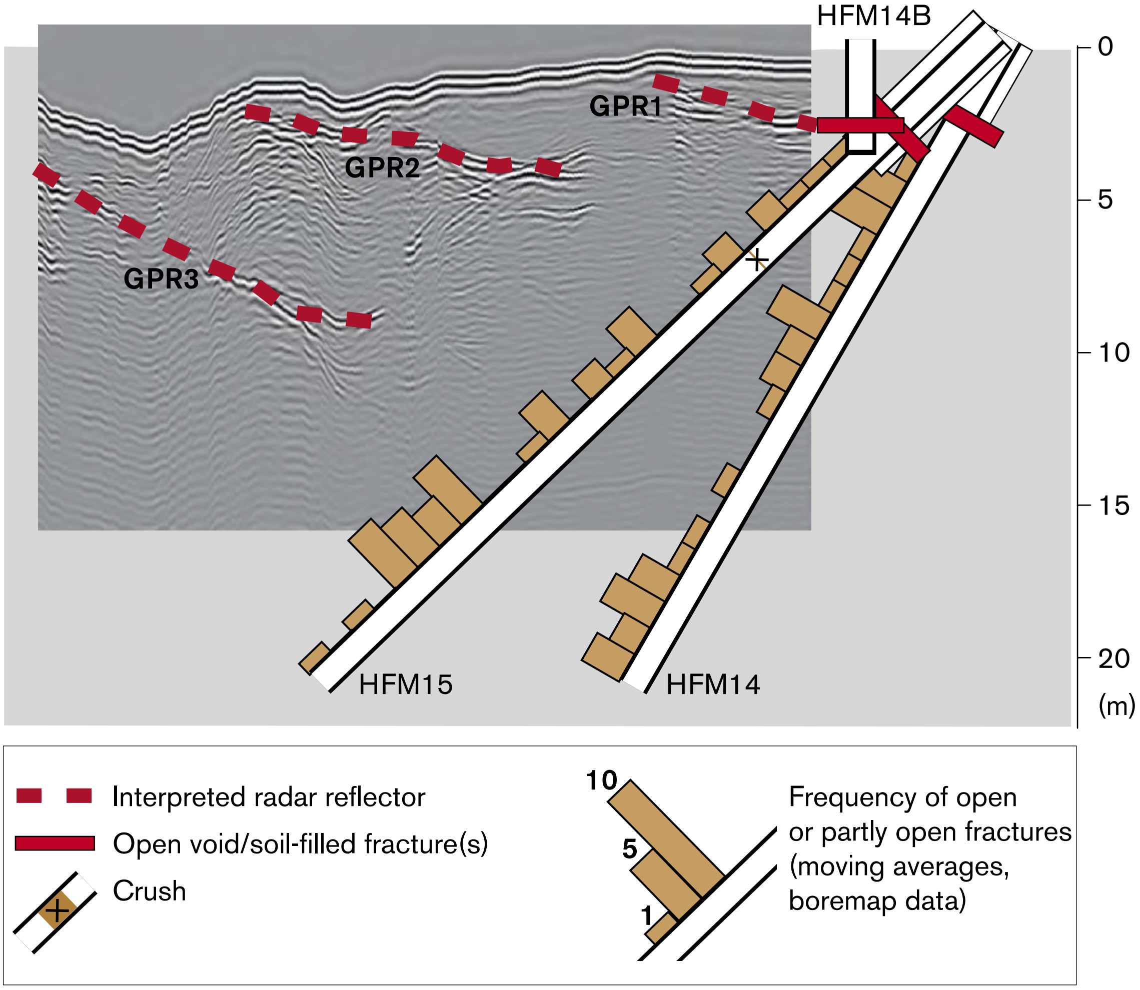


Figure F-11. *NW-SE section of the uppermost 20 m at drill site 5, showing main results from the borehole investigations, together with main fractures inferred from GPR-surveying.*

Figure F-12 shows the same section as Figure F-11, but in a scale such that HFM 14 and HFM15 are displayed to their full lengths (neglecting borehole deviations). As far as fracturing is concerned, borehole data towards depth offer few surprises. Overall fracture frequencies are low. In both HFM14 and HFM15, increased fracturing indicates a possible fracture zone within the approximate depth interval 60–67 m. In HFM14, another similar zone is indicated at 79–90 m. The fractures constituting the inferred zones are largely subhorizontal.

Figure F-12 also indicates hydraulic conditions observed in the boreholes. It is seen that:

- Excluding the open, superficial fractures resulting in surface discharge of drilling water (cf Figure F-6), the first indication of a conductive structure (from flow logging, cf Figure F-10) is observed at about 16.5 m depth in HFM15.
- A number of water bearing structures are found within the approximate interval 40–60 m.

Some of the water bearing structures are highly conductive. Inflows tended to occur distinctly and could in many cases be correlated with individual fractures.

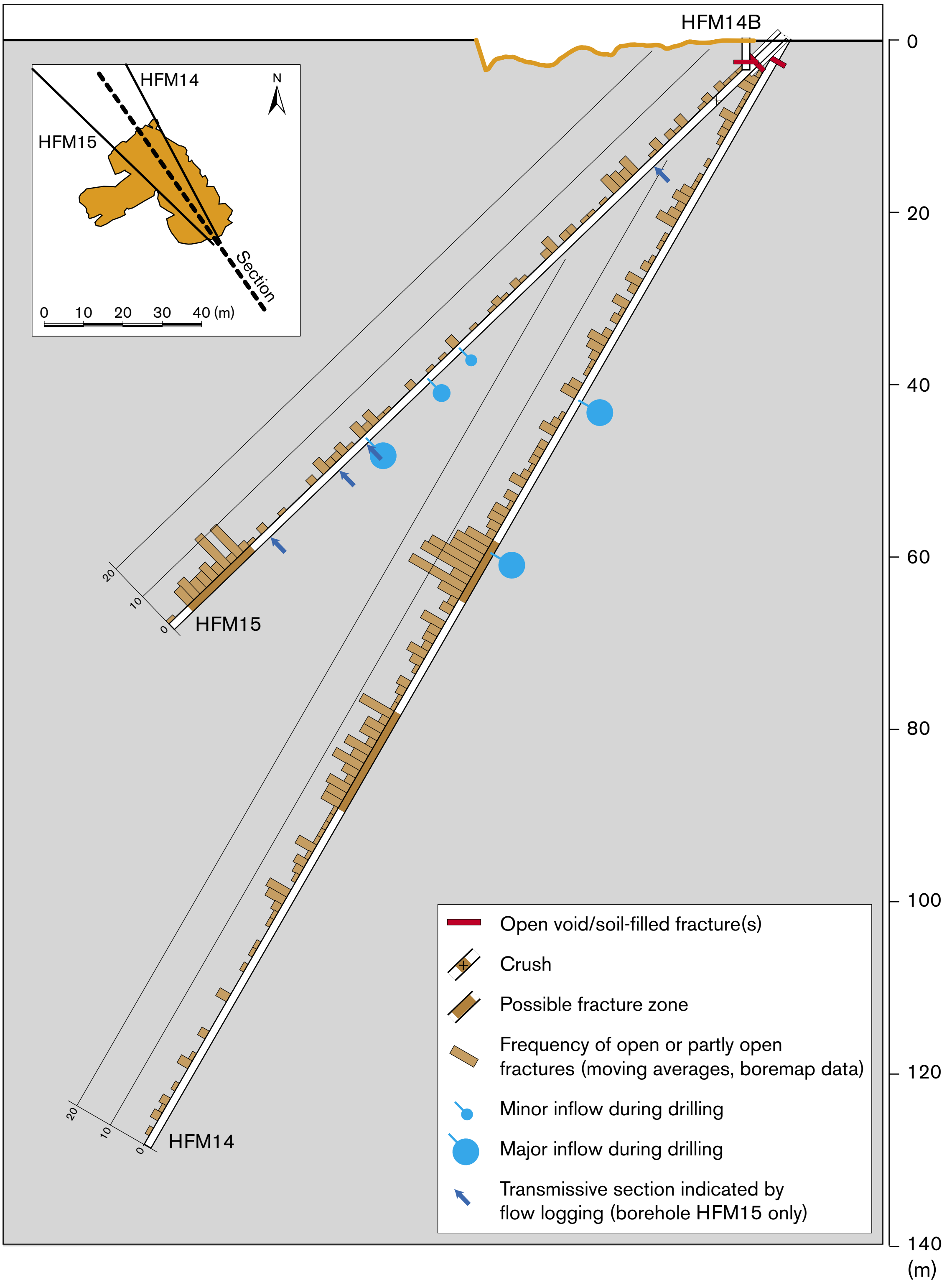


Figure F-12. *NW-SE section of the uppermost 140 m at drill site 5, showing main results from the borehole investigations.*

Another observation that has already been mentioned was that hydraulic connections exist between the holes at drill site 5, and holes several hundreds metres away. Altogether, the hydraulic conditions observed in HFM14 and HFM15 are in accordance with the general pattern that the site investigation work so far has revealed, for the depth interval in question and within the tectonic lens at Forsmark.

The results summarized above should be considered in relation to the main drilling objectives defined, i.e. to investigate primarily the state of fracturing and possible extension towards depth of the anomalous conditions documented at surface. The relevant reference for comparison is the generalized picture of the uppermost c 100 m of the bedrock that has emerged from investigations conducted within the tectonic lens at Forsmark so far. Thus, viewing the percussion borehole data from drill site 5 against this background, it is found that:

- Anomalous conditions similar to those documented at surface (uplift, extreme fracture apertures, sediment filling) were verified to a depth of about 4 m.
- Fractures, though neither of very large aperture nor sediment-filled, that may or may not be related to the surface fracturing were observed down at most 10 m depth.
- For the remainder of the depth interval investigated, there is nothing in the data that indicates conditions deviating from those typically encountered at Forsmark.

These findings strongly suggest that the disturbances observed at drill site 5 are confined to the superficial rock mass.

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Appendix G

The phenomenon of “soil-filled fractures” in crystalline rock, origin and possible impact on a repository

Roland Pusch
Geodevelopment AB

November 2003

Contents

G1 Purpose

In the Forsmark area and in central Umeå (university hospital area), and probably numerous other areas unknown at present, there are gently-dipping soil-filled fractures of unknown origin in the rock at a depth of one or two metres. It is urgent to explain the phenomenon and find out whether it may occur at such depths that it could impact a final repository at a depth of several hundred metres. This report intends to examine possible explanations for the mode of formation of such soil-filled fractures and propose the most likely one. The site in question, was drill site 5 at Forsmark, where SKB intends to drill a deep borehole. At the time of inspection on 28 October 2003, the rock at the site had been uncovered and the surface cleared.

G2 Description

The largest fracture fillings are found in gently-dipping openings with a thickness of several decimetres that mostly face north. Their appearance is illustrated by photographs taken by Kaj Ahlbom. Figure G-1 is an example that shows clear lamination and a low content of coarse particles. In other cases one can see highly angular rock fragments. The density of the material is not known. It is firmly consolidated and appears to have achieved its density by being loaded by the overlying rock, or from heavier loading. Density is the key to understanding the mode of formation.

The bedrock at the inspection site is divided into blocks and sheets with a size of between a cubic metre and several tens of cubic metres. The blocks are separated by large fractures, both steeply- and gently-dipping. Many of the steeply-dipping fractures have been partly emptied of their content of soil material by erosion.

Figure G-1. *Silt layer with rock fragment in horizontal fracture (photo: Kaj Ahlbom). The material is very firmly consolidated but has been slightly loosened up at the surface in this case.*

The broken-up, large block-type character of the rock, the upper surface of which is undulating, indicates that it cannot have been subjected to the high shear stresses that are generated during large-scale glacial advance. However, the area may first have been subjected to the powerful grinding force of an advancing glacier, and then, after deglaciation, exposed to a second glacial advance with a less powerful shear force that only resulted in the minor disturbances and uplifts of rock blocks that can be seen today. The fracture fillings may have been created in either phase.

G3 Possible explanations of origin

The soil fillings are firmly consolidated, and any explanation of their origin must indicate how this compaction took place. The following explanations are feasible:

1. Rock failure

During the glaciation, with an ice thickness of 2–3 km, vertical and horizontal stresses of several tens of MPa were generated in the underlying rock. On deglaciation, the vertical stress in the uppermost rock declined to nearly zero, while the horizontal stress remained more or less the same and caused sheeting of the rock and detachment of rock sheets at the surface. Soil material consisting of loose till material in the lower part of the glacier flowed out of the deep glacial fissures over the detached sheets. Powerful tremors, generated by the large stress changes in connection with unloading of the rock, caused liquefaction, which displaced the rock sheets and caused them to be embedded in the mud, which was consolidated beneath the weight of the rock sheets. The resulting pressure cannot have exceeded about a hundred kPa corresponding to a density of the fracture fillings of no more than 1700–1900 kg/m^3.

This mode of formation is theoretically possible, but the large movements that the rock sheets must have undergone in order for thick soil layers to be present beneath up to 2 m thick slabs could hardly have been as uniform as would be needed to produce the uniformly thick soil layers. There is no question that the horizontal stresses in the bedrock were high after the unloading of the ice, but this refers to greater depths than a few tens of metres. In the rock nearest the surface, close to the rear edge of the retreating glacier, the deformation pattern may instead have led to the dominance of the vertical stress. This is incidentally asserted by Boulton et al. without evidence /1/.

2. Injection of sediments

According to Boulton et al. vertical fractures in the superficial rock were filled with mud seeping down beneath the ice. When the ice retreated, horizontal fractures also began to open up, material was injected under the influence of the hydraulic gradient and sedimented.

This mode of formation may be correct in principle, but the theory does not provide any concrete explanation for the driving force for the injection of soil material and how it could have given rise to uniformly thick layers with a thickness of about 2 dm beneath 2 m thick rock sheets.

3. Large-scale liquefaction

Another possible explanation for the fracture fillings may be that the rock was overlain by poorly consolidated silty till below sea level after the retreat of the glacier, and that series of extremely severe tremors led to breakup of the rock with accompanying separation, uplift and tilting of individual rock sheets and liquefaction of the till accompanied by inflow of loose till material in all fractures. As in the case of mode of formation no 1, liquefaction displaced the rock sheets and embedded them in the mud, which was consolidated beneath the weight of the rock sheets. The resulting pressure cannot have exceeded a hundred or so kPa, corresponding to a density of the fracture fillings of no more than 1700–1900 kg/m^3.

This mode of formation requires very large rock block movements, which do not accord with the moderate opening of vertical fractures seen on the site.

4. Injection into fractures during interstadial

Profiles across the inspected area and the impression on inspection indicate that the fracture-filling material may have entered from the north. The driving force may have been a second glacial advance that forced the material into fractures dipping a few tens of degrees and opened by this penetration. The material may have been till deposited after the retreat of the primary glacier. The resulting density of the filling material injected into the fractures may be about 2000 kg/m^3.

This mode of formation is feasible, but requires a breakup of the rock that should have led to larger and more irregular block movements and not the conspicuously uniform thickness of the observed soil fillings. Nor does the sediment-like structure of the fillings accord with this hypothesis.

5. Hydrological process – artesian conditions

Till bottom material of the retreating glacier was transported by meltwater into gently-dipping fractures that had been opened by high water pressures, a phenomenon known as hydraulic jacking, as a consequence of artesian conditions /2/. The short transport distance should imply that the particles in the soil layers are very angular, which was confirmed by the inspection. Many turbidity currents can have stratification and sediment-like concordant structure of the type shown in Figure G-1.

Figure G-2 shows a case according to this formation hypothesis where the water pressure is generated by meltwater in deep glacial fissures that are in hydraulic contact with both steeply-dipping fractures and sheet fractures.

The water pressure required to achieve uplift of the rock is equal to the pressure in the sheeting joints. In order to lift a 1 m thick rock sheet above sea level, this pressure must be about 30 kPa; for 10 m about 300 kPa; etc. Lifting the 2 m thick rock sheet with underlying fracture filling that was seen at the time of the inspection would thus have required a water pressure of at least 6 m water head (60 kPa) if it was situated above sea level, and about 3.5 m water gauge (35 kPa) if situated below sea level. Since the uplifted sheet must have been situated just outside of the retreating ice wall, two conditions must have been fulfilled:

1. The meltwater could not be released at the ice/bed interface.
2. The ice wall must have been very steep so that there could be deep glacial fissures near the wall.

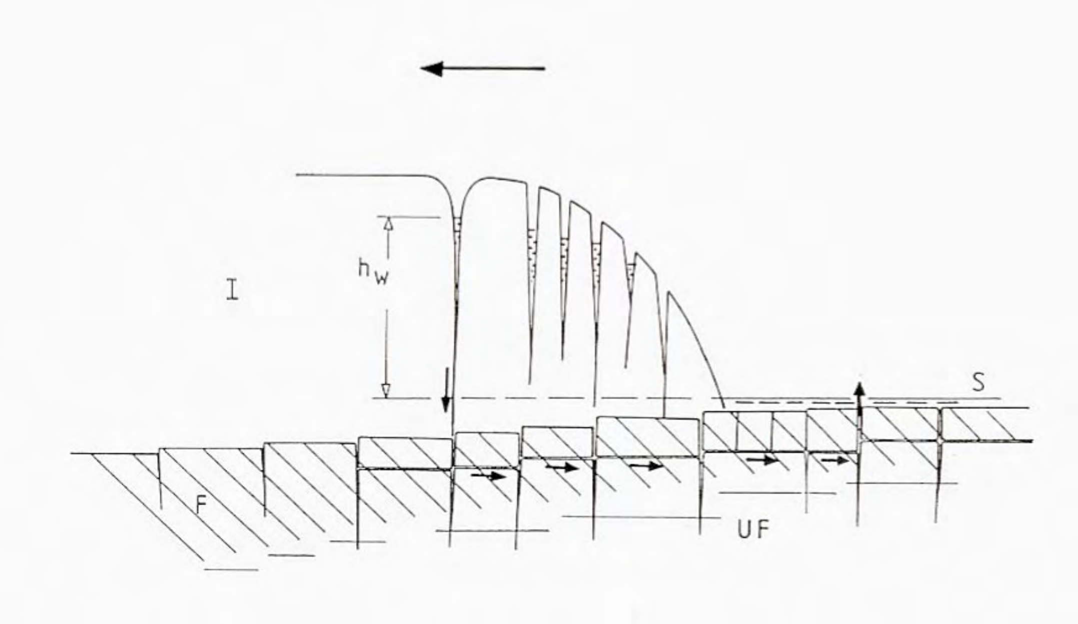

Figure G-2. *Schematic figure of a rapidly retreating glacier. Meltwater is released through interacting steeply- and gently-dipping fractures, which creates artesian conditions /2/.*

The former condition assumes that the ice was frozen to the bed or that the contact was so watertight that the meltwater pressure remained high to distances of metres from the ice wall. The latter condition probably existed if the contact pressure between ice and bed was very high, since the creep properties of the ice may have provided a very good fit between ice and bed. A high contact pressure requires a low water depth.

The condition regarding steepness means that the glacier retreated rapidly. This was the case when the ice margin had passed the Stockholm area (300–400 m/year) and it is therefore logical that the phenomenon with coarse fracture fillings should have been encountered in Forsmark and further north. Further south, the rate was 50–100 m/year (Ramsay). The shape of the retreating glacier can be roughly estimated by comparison with measured large glaciers such as Mer de Glace, Mont Blanc, which has had a steep front, see Figure G-3. An estimation shows that it is possible to approximate the profile of a large steady-state glacier as a parabola with a stable vertical front wall with a height of at least 50 m, and behind this a slope that is determined by e.g. the creep properties of the ice. During retreat, the slope of the ice wall is determined by the same creep properties, which should give the same slope with the exception of calving along steeply-dipping glacial fissures near the free wall. Photos from recent Greenlandic glaciers show that the ice wall can be very steep, with a height of about 50 m.

With this mode of formation, the fracture fillings would have consolidated under the weight of the rock sheets when the artesian overpressure had dissipated. As an example, a 2 m rock sheet above sea level or about 4 m below sea level created an effective pressure of about 60 kPa, which cannot have produced a higher density in the soil material than about 1700–1900 kg/m^3 in the water-saturated state. For a 20 m rock sheet above sea level or about 40 m below sea level, the equivalent effective pressure would have been about 600 kPa, which could have produced a density of at least 2000 kg/m^3 in the water-saturated state. A comparison can be made with the density of the basal till, which is probably at least 2200 kg/m^3.

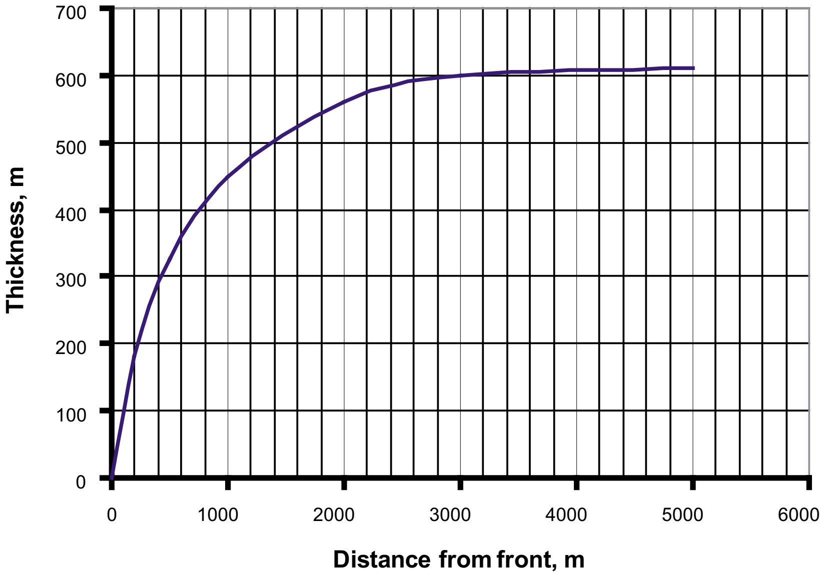

Figure G-3. *Example of the shape of a large glacier (Mer de Glace, Mont Blanc).*

This mode of formation is judged to be the most likely. The fact that the inspected rock volume in Forsmark has poor continuity, i.e. is divided into smaller blocks separated by wide, steeply-dipping fractures, can be explained by the fact that the uplift was unevenly distributed. If this was the case when the glacier advanced, the loose blocks would have been cleared away, which means that the fracture fillings are probably Finiglacial according to the described hypothesis.

G4 Discussion and conclusions

Most likely origin

Alternative 5 above provides an explanation for the driving force behind the formation of the fracture filling and quantifies the artesian pressure that is required to cause inflow of till material in the fractures. Thus, it is clear from the FEM-calculation in Figure G-4 that water-filled, 50 m deep fractures near the ice wall mobilize a water pressure in a potentially expandable sheeting joint just outside the ice wall of up to 300 kPa. According to the explanation given above, this could lift a rock sheet below sea level with a thickness of about 20 m.

Determination of the density of the fracture fillings at the site can provide a better basis for judging which of the formation hypotheses is most reasonable: For 1), 2), 3) and 5) about 1700–1900 kg/m^3 and for 4) about 2000 kg/m^3. A verification that the formation of the fracture fillings is consistent with processes associated with the retreat of the glacier and does not have an older origin can be obtained by determining the density of a representative fracture filling and comparing it with the density of the basal till in this area.

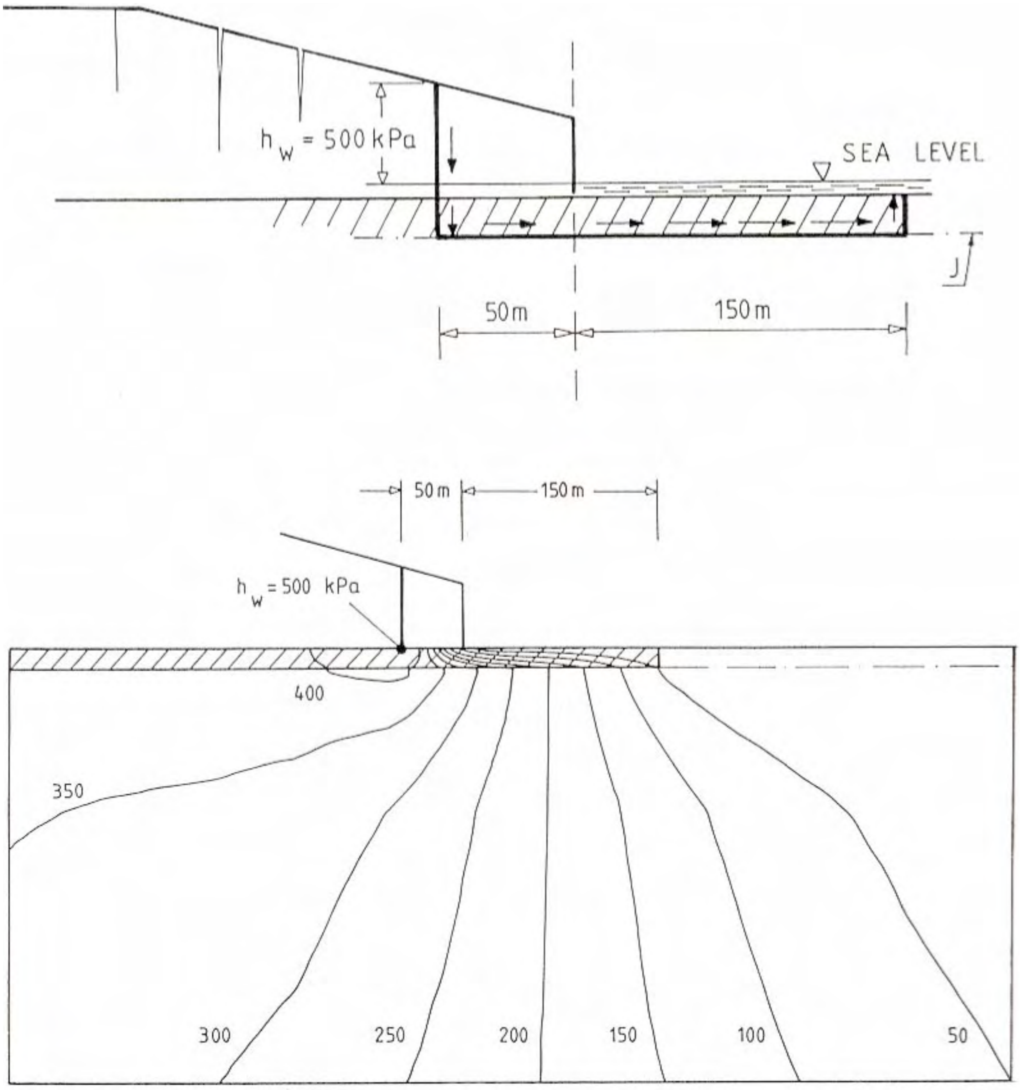

Figure G-4. *Outflow of meltwater beneath hydraulic gradients formed at the lower part of a retreating glacier. Top: Schematic illustration with meltwater that creates an overpressure of 500 kPa in relation to sea level. J is a gently-dipping fracture that is opened and filled with till material according to mode of formation no 5. Bottom: Heads calculated by the FEM method.*

Possible occurrence at greater depth

The most likely mode of formation entails that lifting of rock sheets cannot take place at great depth. As an extreme and in practice improbable case, it can be assumed that the ice wall of the retreating glacier is vertical and 150 m high. This could create an artesian pressure of 1.5 MPa, which can cause uplift of a rock sheet with a thickness of 60 m above sea level and about 100 m below sea level. In practice, however, the height of the ice wall can hardly exceed 50 m and cannot cause uplift of more than a 20 m rock sheet below sea level. **It can therefore be concluded with good certainty that the phenomenon of uplift and soil-filling of fractures cannot occur at depths greater than about 50 m.**

G5 Soil mechanics investigation

By determining the density of undisturbed fracture-filling material and the basal till in the excavation pit, information can be obtained on the material's stress history. Such an investigation should be carried out in order to validate the hypotheses regarding mode of formation.

The investigation should include (cf Figure G-5):

1. Uncovering of an approximately 2 dm thick layer and excavation to such a geometric shape that the volume can be measured and weighing of the excavated material can be performed, to allow the density to be calculated. The layer can be uncovered as shown in the figure, by first slot drilling 20–40 vertical holes in the 2 m thick rock sheet, then removing the rock in the wedge layer by layer by slot drilling 5 holes horizontally at levels spaced at about 30 cm and use a Darda hydraulic splitter, wedging or expanding grout until the soil filling has been exposed. To preserve the layer undisturbed, the vertical holes are plugged with wooden rods.

2. Equivalent sampling of a few hundred litres of basal till for density determination.

3. Determination of water content by drying of all material to 105°C. This allows the porosity, and thereby the density, to be determined.

4. Sending 5 kg of representative soil material from the fracture filling for load testing at a soil mechanical laboratory.

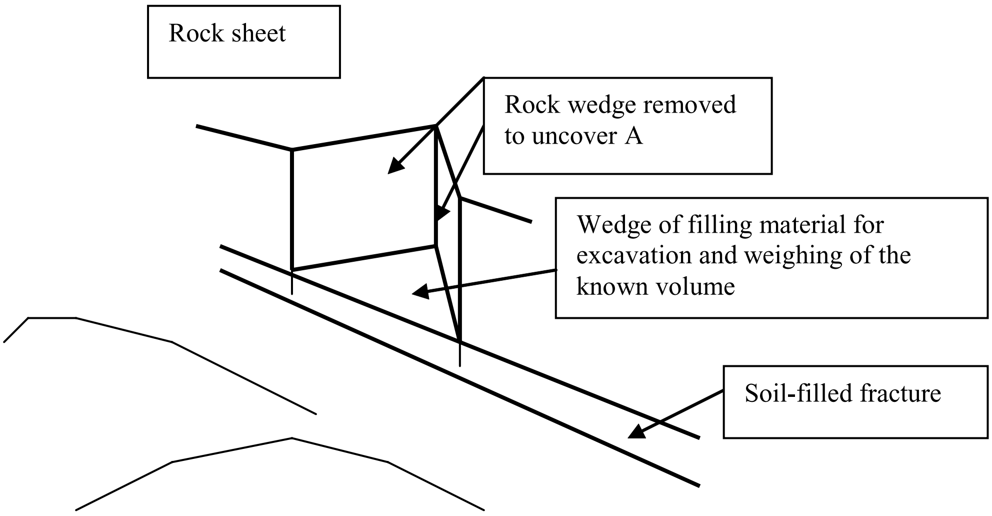

Figure G-5. *Method for determination of the density of fracture filling. 1) The rock wedge is removed to the top surface of the filling, by vertical and horizontal drilling with a pneumatic drill; the vertical holes are driven through the layer and the part through the filling is plugged. 2) The filling is dug out within a well-defined volume and the excavated material is weighed in the naturally moist- and dried states for calculation of density and porosity.*

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