Site Characterization and Validation
Stage 2 — Preliminary Predictions

O. Olsson
ABEM AB, Sweden
J. Black
Golder Associates, U. K.
J. Gale
Fracflow Inc., Canada
D. Holmes
British Geological Survey, U. K.

May 1989
This report concerns a study which was conducted for the Stripa Project. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

A list of other reports published in this series is attached to the end of this report. Information on previous reports is available through SKB.
A draft version of this report was circulated to the members of the Stripa Project Task Force on Fracture Flow Modelling and to the SCV Project Investigators in September 1988. The authors have received comments on the report and have included suggested modifications and clarifications where appropriate. During the final editing of the report the investigations at the SCV site have continued and that data will to some extent provide checks on the predictions made in this report. However, the predictions made in this report are based on the Stage I (Preliminary site characterization) data and predictions have not been modified to accommodate any data collected after September 1988.
ABSTRACT

The Site Characterization and Validation (SCV) Project is designed to assess how well we can characterize a volume of rock prior to using it as a repository. The programme of work focuses on the validation of the techniques used in site characterization. The SCV Project contains 5 stages of work arranged in two "cycles" of data-gathering, prediction, and validation. The first stage of work has included drilling of 6 boreholes (N2, N3, N4, W1, W2, and V3) and measurements of geology, fracture characteristics, stress, single borehole geophysical logging, radar, seismics, and hydrogeology.

The rock at the SCV site is granite with small lithological variations. Based essentially on radar and seismic results 5 "fracture zones" have been identified, named GA, GB, GC, GH, and GI. They all extend across the entire SCV site. They are basically in two groups (GA, GB, GC and GH, GI). The first group are aligned N40°E with a dip of 35° to the south. The second group are aligned approximately N10°W dipping 60°E.

From the stochastic analysis of the joint data it was possible to identify three main fracture orientation clusters. The orientation of two of these clusters agree roughly with the orientation of the main features. Cluster B has roughly the same orientation as GH and GI, while features GA, GB, and GC have an orientation similar to the more loosely defined cluster C. The orientation of the third cluster (A) is northwest with a dip to northeast.

It is found that 94 % of all measured hydraulic transmissivity is accounted for by 4 % of the tested rock, not all of this "concentrated" transmissivity is within the major features defined by geophysics. When the hydraulic connections across the site are examined they show that there are several well-defined zones which permit rapid transmission of hydraulic signals. These are essentially from the northeast to the southwest.

Keywords: Site characterization, remote sensing, fracture zones, joint statistics, joint surface characteristics, conceptual model, hydrochemistry.
SUMMARY AND CONCLUSIONS

The Site Characterization and Validation (SCV) Project is designed to assess how well we can characterize a volume of rock prior to using it as a repository. The programme of work is designed to focus on the problem of validating the correctness of the techniques used in the site characterization. The central aim of the programme is to predict groundwater flow in a specific volume of rock and to compare these predictions with data from field measurements. The distribution of water flow into a drift (tunnel) will be predicted, the drift will be excavated, the inflows will be measured and compared with prediction.

The SCV Project contains 5 stages of work arranged in two "cycles" of data-gathering, prediction, and validation (comparison of observation against prediction). This report summarizes the first "round" of data gathering and makes some outline predictions based on those data. The period of data gathering, beginning in summer 1988 with the excavation of the access drift and the drilling of the "C" and "D" boreholes, will provide the measurements against which these outline predictions will be compared.

The first stage of work has included drilling of 5 boreholes (N2, N3, N4, W1, W2, and V3) and measurements of geology, fracture characteristics, stress, single borehole geophysical logging, radar, seismics, and hydrogeology. This work is reported individually (cf. Section 1.4) as well as summarized here.

The site for the SCV Project is located between 340 m and 410 m below the ground to the northwest of the mine opening and the sites of previous experiments. The figure on the next page shows the location of the SCV block in relation to existing drifts, boreholes, and the ore body. The mine is viewed from the south. The rock is granite with small lithological variations. The granite is traversed by regionally visible fracture zones with spacings around a kilometre. This compares with the 125 m sides of the volume being investigated. The mine opening affects the regional hydrogeology and the regional stress field. It intercepts regional groundwater flow paths, some of which are up to 10 km in length, and over the period of mine operations it has reversed some flow away from Lake Råsvalen.
The SCV site lies within a local groundwater flow system where the mine acts as a sink. In this system "young" low salinity groundwater flows downwards towards the mine and mixes with "older" more saline water flowing upwards from depth. Near the surface, waters are almost exclusively "young", whilst at depth (i.e. >400 m) waters are "old". The site therefore lies within a zone of mixing between about 200 and 400 m below ground. This is reflected in the hydrochemistry of the site. The SCV site also lies within a region of stress realignment with more or less unmodified regional stress in the northern half of the site and about 30° realignment in the south.

The predictions concerning water inflows will be based on a numerical model of the mine. In reality, this is a set of 4 models at increasing detail; a regional model, a sub-region model, a "mine" model, and a "site" model. The first two parts were completed during the previous phase of the Stripa Project. The large region model assumes boundary conditions such as the topography of the water table and surrounding impermeable borders. The head and flow distribution is then calculated within the modelled region. The boundary heads and flows for the three more detailed models are all based on the results obtained from the model "next up" in the series. All of these models are finite element equivalent porous medium models. However, at the most detailed level, the "site" model, a region will be modelled using a fracture network approach. This is the region of the proposed validation drift. At all stages in the modelling some fracture zones will be included explicitly as regions of distinctly different properties. Hence, the site needs to be characterized in terms of highly transmissive "fracture zones" and "background rock".

The major structural features within the SCV site have been identified, within this phase of work, primarily on the basis of geophysical remote sensing (i.e. single borehole radar and crosshole radar and seismics). Major features have been selected mainly on how extensive they are as observed in tomograms. It has also been found that there is a general correlation between radar "slowness" tomograms and transmissivity. Using this geophysical information 5 "fracture zones" have been identified, named GA, GB, GC, GH, and GI. They all extend across the entire SCV site. They are basically in two groups (GA, GB, GC and GH, GI). The first group are aligned N40°E with a dip of 35° to the south. The second group are aligned approximately N10°W dipping 60°E. Both sets are in the order of 50 m apart but there are also other minor features in between. The figure below shows a
Of the two groups, the second more steeply dipping set (i.e. GH and GI) are more extensive and more continuous. There are other features with a northwesterly strike (e.g. RK) but they are less extensive and have not been included deterministically in the conceptual model. All features are irregular and appear in the tomograms as series of connected patches rather than as well-defined planar zones.

The rest of the rock has been characterized in terms of the occurrence of fractures. Their geometric properties (spacing, orientation, and trace length) have been measured both along scan lines in the drifts as well as in the core from the boreholes. Their hydraulic properties have been measured in the boreholes.

It is clear that there are several biases in the data. Firstly, there are two subhorizontal borehole orientations which do not sample the vertical direction very well. Secondly the drifts have a limited dimension which censors the data on trace lengths. However, although there are detailed
systematic variations across the site there are essentially two well measured clusters (Clusters A and B) and a third poorly measured group (Cluster C). The fractures of Cluster A have a wide range of orientations with an average strike orientation of about N45W and the fractures are steeply dipping in either the northeasterly or the southwesterly direction. The fractures in Cluster B have either easterly or westerly dips that are practically vertical with a strike of about N10 degrees. The third group, Cluster C, are subhorizontal and not very well-measured. The trace length data are strongly affected by censoring and truncation and it was only possible to make the necessary correction for Cluster C. The spacings between the clusters vary and these differences are easily seen in the different number of fractures intercepted by the boreholes of westerly and northerly orientation.

The hydraulics of the fractures vary depending on orientation and it seems that the mean aperture of the fractures penetrated by the W boreholes is larger than that penetrated by the N boreholes. Interpretation according to the Clusters A, B, and C is not completed.

The accurate prediction of water inflows, based on geophysical remote sensing, is dependent on the correlation between significant geophysical features and hydrogeological features. Unfortunately major geophysical features are defined by their extensiveness whilst hydraulic features result from single borehole tests. Single borehole hydraulic tests measure the hydraulic properties immediately surrounding the test borehole. In contrast it is known that significant extensive geophysical features are patchy. Hence it can be expected that identification of major geophysical features is a reasonable prediction of single borehole performance but a better prediction of whole drift performance (where the effect of patchiness (or channeling) is reduced).

Examining the correlation between the identified geophysical features and single borehole hydraulic results shows some interesting features. Firstly the five major features are identified as having a thickness between 3 and 8 metres where they cross the five N and W boreholes. This accounts for 93 m of the 868 m of tested borehole. This 11 % of the boreholes contains 57 % of the total borehole transmissivity. However, the transmissivity is much more unevenly distributed with 94 % of the transmissivity measured in 32 one metre sections (i.e. 4 % of the measured length). Two of the most transmissive sections accounting for 33 % of the measured transmissivity
were close to but not contained within geophysical features. If these are included within the zones to which they are adjacent then geophysical features account for 90% of the measured transmissivity. The idea of proximity is inexact but should be justified when considering inflows to a drift.

There is at present limited evidence of crosshole responses between the boreholes of the SCV site. However, if this is combined with the head data gathered during the single borehole testing and with the long term Piezomac (head) data some factors are clear. First of all there are rapid pressure responses right across the site with speeds up to 14 metres per minute seen in one zone. Secondly there seems to be a general flow of water from the north (to the NW of the 3D Drift) towards the south and southwest. A large region of low head is found in northwest (i.e. the furthest ends of W2 and N4). The explanation for this large region of reduced heads at some distance from the mine must lie in the presence of at least one highly transmissive feature draining towards the mined cavity and probably oriented subhorizontally. This is not an orientation which is well sampled by the existing borehole layout. This also presents a 'geophysical' prediction problem since small errors in orientation will result in large differences in intersection position.

A series of predictions are put forward in the final Chapter of the report. These include:

- the intersection of major features with the "C" and "D" boreholes and the access drift.
- the geological characteristics of these features where observed.
- the fracture characteristics sampled by the new boreholes and drifts.
- the hydraulic properties of the new boreholes.
- the head gradients likely to be measured in the new boreholes.
# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOREWORD</td>
<td>i</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>SUMMARY AND CONCLUSIONS</td>
<td>iii</td>
</tr>
<tr>
<td>CONTENTS</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xviii</td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 BACKGROUND</td>
<td>1</td>
</tr>
<tr>
<td>1.2 PREVIOUS WORK</td>
<td>5</td>
</tr>
<tr>
<td>1.3 THE CONCEPTUAL MODEL</td>
<td>5</td>
</tr>
<tr>
<td>1.4 LAYOUT OF THE REPORT</td>
<td>7</td>
</tr>
<tr>
<td>2 THE SITE OF THE SCV PROJECT</td>
<td>8</td>
</tr>
<tr>
<td>2.1 GEOLOGY</td>
<td>8</td>
</tr>
<tr>
<td>2.1.1 Regional geology</td>
<td>8</td>
</tr>
<tr>
<td>2.1.2 The Stripa granite</td>
<td>9</td>
</tr>
<tr>
<td>2.1.3 Leptite and iron ore</td>
<td>11</td>
</tr>
<tr>
<td>2.1.4 Fractures and fracture zones</td>
<td>11</td>
</tr>
<tr>
<td>2.2 LAYOUT</td>
<td>18</td>
</tr>
<tr>
<td>2.3 HYDROGEOLOGICAL SETTING</td>
<td>23</td>
</tr>
<tr>
<td>2.3.1 Importance of hydrogeological setting</td>
<td>23</td>
</tr>
<tr>
<td>2.3.2 Regional flow</td>
<td>23</td>
</tr>
<tr>
<td>2.3.3 Hydrochemistry and regional flow</td>
<td>28</td>
</tr>
<tr>
<td>2.4 STRESS FIELD</td>
<td>30</td>
</tr>
<tr>
<td>3 MAJOR STRUCTURAL FEATURES</td>
<td>34</td>
</tr>
<tr>
<td>3.1 IDENTIFICATION OF MAJOR FEATURES</td>
<td>34</td>
</tr>
<tr>
<td>3.1.1 Introduction</td>
<td>34</td>
</tr>
<tr>
<td>3.1.2 Radar technique</td>
<td>36</td>
</tr>
<tr>
<td>3.1.3 Seismic technique</td>
<td>47</td>
</tr>
<tr>
<td>3.2 SINGLE BOREHOLE RESULTS</td>
<td>52</td>
</tr>
<tr>
<td>3.2.1 Evidence of fracture zones in the drillcore</td>
<td>52</td>
</tr>
<tr>
<td>3.2.2 Geophysical logging evidence</td>
<td>53</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>3.3</td>
<td>HYDRAULIC EVIDENCE OF FRACTURE ZONES</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Crosshole hydraulic responses</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Head distribution</td>
</tr>
<tr>
<td>3.4</td>
<td>HYDROCHEMISTRY</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Results</td>
</tr>
<tr>
<td>3.4.3</td>
<td>Interpretation in terms of major features</td>
</tr>
<tr>
<td>3.5</td>
<td>DISCUSSION OF EVIDENCE</td>
</tr>
<tr>
<td>3.5.1</td>
<td>Feature GA</td>
</tr>
<tr>
<td>3.5.2</td>
<td>Feature GB</td>
</tr>
<tr>
<td>3.5.3</td>
<td>Feature GC</td>
</tr>
<tr>
<td>3.5.4</td>
<td>Feature GH</td>
</tr>
<tr>
<td>3.5.5</td>
<td>Feature GI</td>
</tr>
<tr>
<td>3.5.6</td>
<td>Features RK, SK, RL, and SL</td>
</tr>
<tr>
<td>3.6</td>
<td>SUMMARY DESCRIPTION OF MAJOR FEATURES</td>
</tr>
<tr>
<td>4</td>
<td>FRACTURE SETS</td>
</tr>
<tr>
<td>4.1</td>
<td>INTRODUCTION</td>
</tr>
<tr>
<td>4.1.1</td>
<td>General fracture characteristics</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Fracture orientation</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Variability in fracture orientation</td>
</tr>
<tr>
<td>4.1.4</td>
<td>Fracture trace lengths</td>
</tr>
<tr>
<td>4.1.5</td>
<td>Fracture spacings</td>
</tr>
<tr>
<td>4.2</td>
<td>HYDRAULIC PROPERTIES OF FRACTURE SETS</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Testing procedures</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Results of hydraulic testing</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Interpretation of fracture orientations</td>
</tr>
<tr>
<td>4.3</td>
<td>MECHANICAL PROPERTIES OF FRACTURE SETS</td>
</tr>
<tr>
<td>5</td>
<td>DISCUSSION</td>
</tr>
<tr>
<td>5.1</td>
<td>DIVISION INTO MAJOR FEATURES AND ROCK MASS</td>
</tr>
<tr>
<td>5.2</td>
<td>CORRELATION OF HYDRAULIC AND GEOPHYSICAL PROPERTIES</td>
</tr>
<tr>
<td>5.3</td>
<td>UNACCOUNTED-FOR SINGLE BOREHOLE ANOMALIES</td>
</tr>
<tr>
<td>6</td>
<td>PREDICTIONS</td>
</tr>
<tr>
<td>6.1</td>
<td>INTRODUCTION</td>
</tr>
<tr>
<td>6.2</td>
<td>LAYOUT OF STAGE III BOREHOLES AND ACCESS DRIFT</td>
</tr>
<tr>
<td>6.3</td>
<td>INTERCEPTS OF MAJOR FEATURES BY NEW BOREHOLES AND DRIFTS</td>
</tr>
<tr>
<td>6.3.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>6.3.2</td>
<td>Access drift</td>
</tr>
<tr>
<td>6.3.3</td>
<td>C and D boreholes</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES**

| Figure 1.1 | Location of the SCV-site relative to previous experimental areas and the mined-out cavity. Solid: 360 m level, dashed: 335 m level. | 4 |
| Figure 2.1 | Regional geology of the area around Stripa (from Lundström, 1983). | 14 |
| Figure 2.2 | Detailed geology of the immediate area around the Stripa mine. | 15 |
| Figure 2.3 | Vertical geologic section through the Stripa mine. The location of the profile is shown in Figure 2.2. | 16 |
| Figure 2.4 | Major structural features in the Stripa area on a regional scale (from Lundström, 1983). | 17 |
| Figure 2.5 | Perspective view of mined out area in relation to the SCV-site. | 21 |
| Figure 2.6 | Map of the SCV-site indicating the location of the "boundary boreholes", boreholes drilled prior to the start of the SCV Project, and existing mine workings. | 22 |
| Figure 2.7 | Map of regional water table around the Stripa Mine with approximate directions of groundwater flow. | 25 |
| Figure 2.8 | Finite element mesh and simplified geology for the regional model showing the location of the major lakes and fracture zones (heavy black lines). | 26 |
| Figure 2.9 | Finite element mesh and simplified bedrock geology for the sub-region model showing the mine tailings pond, Lake Råsvalen, fracture zones (heavy black lines), and the Stripa mine ventilation shaft. | 27 |
| Figure 2.10 | Postulated flow in region with hydrochemical implications (cf. the geological cross section of the mine shown in Figure 2.3). | 29 |
| Figure 2.11 | Summary of the stress measurements performed in the Stripa mine (1977-1988). | 32 |
| Figure 2.12 | Calculated principal stress distribution at the 360 m level in the vicinity of the SCV site (from Chan and others, 1981). | 33 |
Figure 3.1  Radar reflection map from borehole N2 measured with a centre frequency of 22 MHz. Reflections marked RA, RB, RC, RK, and RH are caused by features (fracture zones) included in the radar model of the SCV-site. The strong curved reflection is caused by the 3D drift.

Figure 3.2  Residual attenuation tomogram (22 MHz) for the plane defined by the boreholes N2-N3-N4. The location of the major and minor features included in the radar model of the SCV-site are indicated.

Figure 3.3  Residual attenuation tomogram (22 MHz) for the plane defined by the boreholes W1-W2. The location of the major and minor features included in the radar model of the SCV-site are indicated.

Figure 3.4  Residual slowness tomogram (22 MHz) for the plane defined by the boreholes N2-N3-N4. The location of the major and minor features included in the radar model of the SCV-site are indicated.

Figure 3.5  Residual slowness tomogram (22 MHz) for the plane defined by the boreholes W1-W2. The location of the major and minor features included in the radar model of the SCV-site are indicated.

Figure 3.6  Seismic velocity tomogram for the plane defined by the boreholes N2-N3-N4. Major features are indicated in solid lines while minor features are dashed.

Figure 3.7  Seismic velocity tomogram for the plane defined by the boreholes W1-W2. Major features are indicated in solid lines while minor features are dashed.

Figure 3.8  Processed seismic reflection profile with source in the drift at the start of borehole W2. Receiver is moved in W1. The features are seen as trends rather than as isolated events.

Figure 3.9  Composite log of data collected along borehole N2.

Figure 3.10 Composite log of data collected along borehole N3.

Figure 3.11 Composite log of data collected along borehole N4.

Figure 3.12 Composite log of data collected along borehole W1.

Figure 3.13 Composite log of data collected along borehole W2.
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.14</td>
<td>Responses observed in adjacent boreholes due to short-term disturbances in borehole W2.</td>
</tr>
<tr>
<td>3.15</td>
<td>Map of measured heads between 335 m and 385 m below ground in the area of the SCV Site. Datum is 360 m level.</td>
</tr>
<tr>
<td>3.16</td>
<td>A schematic illustration of the hydraulic conductivity and the borehole sections which have been sampled (shaded).</td>
</tr>
<tr>
<td>3.17</td>
<td>The saline water (A2) is flowing up in the vertical fracture zone GH because of the drainage of the mine. In the subhorizontal fracture zone GB the saline water (A2) is mixed with the non-saline (B) water. The result of mixing is the water of A2-type.</td>
</tr>
<tr>
<td>3.18</td>
<td>Location of major features contained in the conceptual model in the N2-N3-N4 plane.</td>
</tr>
<tr>
<td>3.19</td>
<td>Location of major features contained in the conceptual model in the W1-W2 plane.</td>
</tr>
<tr>
<td>3.20</td>
<td>Location of major and minor features included in the conceptual model of the SCV-site at the 360 m level of the mine.</td>
</tr>
<tr>
<td>3.21</td>
<td>Location of major and minor features included in the conceptual model of the SCV-site at the 385 m level of the mine.</td>
</tr>
<tr>
<td>4.1</td>
<td>Map showing location of boreholes, scanlines and the boundaries of the six subregions used for assessing the overall variation in fracture geometry at the SCV site.</td>
</tr>
<tr>
<td>4.2</td>
<td>Frequency of fractures per metre and RQD values for the three N boreholes shown in their correct relative position. These plots are based on the coated, sealed, and induced fractures and have been calculated using a moving average with a base length of 1.0 m and an increment of 0.2 m.</td>
</tr>
<tr>
<td>4.3</td>
<td>Frequency of fractures per metre and RQD values for the two W boreholes shown in their correct relative position. These plots are based on the coated, sealed, and induced fractures and have been calculated using a moving average with a base length of 1.0 m and an increment of 0.2 m.</td>
</tr>
</tbody>
</table>
Figure 4.4  Plot of poles to fracture planes for all fractures from the scanline mapping program. This contour plot indicates three main clusters of fracture sets, a steeply dipping NNE trending set, a steeply dipping NW trending set, and a subhorizontal set.

Figure 4.5  Plot of the blind zones for each scanline orientation, assuming a blind zone of 20 degrees on either side of the scanline.

Figure 4.6  Contour plots of poles to fracture planes for all boreholes, N2, N3, N4, W1, and W2.

Figure 4.7  Composite plot of blind zones for the two borehole orientations. This plot shows that the sub-horizontal fracture set is not well sampled by the N and W boreholes.

Figure 4.8  Contour plots of poles to fracture planes for the combined data set of five boreholes and the scanline fracture data.

Figure 4.9  Pole plots of 60 fractures from each of the N and W boreholes at each of the points where the W boreholes cross over the N boreholes in the plan view.

Figure 4.10  Plot for the mean pole directions for the clusters in each set of 120 fracture planes from the points where the W boreholes cross over the N boreholes. The symbols indicate the location of each cluster from each set of data.

Figure 4.11  Plot of the mean pole directions for (a) all of the clusters in the SCV block and (b) the clusters in each of the sub-regions. The statistics for each cluster are given in Gale and Stråhle, 1988.

Figure 4.12  Histograms of trace lengths measured along the drifts as part of the scanline mapping programme for each of the three main cluster groups showing the degree of censoring.

Figure 4.13  Histogram of trace lengths measured along drifts as part of the scanline mapping program for each of the three main cluster groups showing the termination modes.

Figure 4.14  Histogram of fracture spacings computed from the borehole fracture data for each of the three main cluster groups.
Figure 4.15 General diagram of hydraulic testing equipment.

Figure 4.16a The distribution of transmissivity in the boreholes W1 and W2 according to location at the SCV site.

Figure 4.16b The distribution of transmissivity in the boreholes N2, N3, and N4 according to location at the SCV site.

Figure 4.17a The dependance on transmissivity of the number of "coated fractures per test section in boreholes W1 and W2.

Figure 4.17b The dependance on transmissivity of the number of "coated fractures per test section in boreholes N2, N3, and N4.

Figure 4.18 Histogram of joint compressive strength for joint set no. 2, strike N-S. 122 observations, median value 140 MPa.

Figure 4.19 Histogram of residual friction angle $f_\alpha$ for joint set no. 2. Median value 25.5°.

Figure 4.20 Histogram for joint roughness coefficient for joint set no. 2. Median value 6.9.

Figure 4.21 Cyclic joint behaviour for normal loading of joint set no. 2 with corresponding conductivity change.

Figure 4.22 Shear stress, dilatation, and conductivity change against shear deformation for normal stress of 5, 15, and 25 MPa. Joint set no. 2.

Figure 5.1 Distribution of hydraulic conductivity in N and W boreholes.

Figure 5.2 Summary diagram showing location of geophysical features and hydraulically conductive zones in the boreholes.

Figure 5.3 Sonic and hydraulic conductivity logs from borehole N4 and crossplot of data.

Figure 6.1 Location of C-boreholes, access drift, and validation drift. Solid; 360 m level, dashed; 410 m level.

Figure 6.2 Vertical section at the coordinate X=440 m in the mine system. Location of C-holes, validation and access drift are indicated in relation to the major features GB and GH.

Figure 6.3 Perspective view of main features in relation to C boreholes and the access and validation drifts. Composite of all features (above) and feature GH (below).
Figure 6.4 Perspective view of main features in relation to C boreholes and the access and validation drifts. Feature GA (above) and feature GB (below).

Figure 6.5 Perspective view of main features in relation to C boreholes and the access and validation drifts. Feature GC (above) and feature GI (below).

Figure 6.6 Prediction of hydraulic conductivity in the 3 boreholes C1, C2, and C3.

Figure 6.7 Contour plot of the poles to fracture planes for all boreholes within the SCV block boundaries. Additional fractures have been added to the data set to correct for orientation bias in the form of blind zones. Each dot represents the pole to a fracture plane. Contours are spaced 0.1 density units.

Figure 6.8 Predicted fracture geometry for (a) C1 and (b) C2. These plots are not corrected for orientation bias. The number of coated and sealed fractures for each borehole are given on each plot.

Figure 6.9 Predicted fracture geometry for (a) C3 and (b) D1. These plots are not corrected for orientation bias. The number of coated and sealed fractures for each borehole are given on each plot.

Figure 6.10 Plan view of the "Mine model" finite element mesh for the 3-D porous media model that will be used to calculate the hydraulic head boundary conditions for the 3-D discrete fracture model. The thickness of each of the sixteen layers in the model are shown in the figure. Also, the area included in this model can be compared in the inset to its size in the sub-model region of Gale et. al. (1987). Note the location of the Ventilation and Z shafts, the validation (V) drift and the heavy lines marking the location of the fracture zones.
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.1</td>
<td>Position of boreholes W1, W2, N2 - N4, and V3, in the local mine coordinates. Bearing from mine north (in degrees), plunge below horizontal plane (in degrees), length (m), together with date for start and completion of drilling.</td>
<td>20</td>
</tr>
<tr>
<td>Table 2.2</td>
<td>Coordinates of the 8 corners of the block to be modelled.</td>
<td>20</td>
</tr>
<tr>
<td>Table 3.1</td>
<td>Main orientations of features crossing the SCV site inferred from seismic reflection analysis.</td>
<td>48</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>The classification of the sampled groundwaters.</td>
<td>65</td>
</tr>
<tr>
<td>Table 3.3</td>
<td>Summary of data associated with the feature GA.</td>
<td>74</td>
</tr>
<tr>
<td>Table 3.4</td>
<td>Summary of data associated with the feature GB.</td>
<td>76</td>
</tr>
<tr>
<td>Table 3.5</td>
<td>Summary of data associated with the feature GC.</td>
<td>77</td>
</tr>
<tr>
<td>Table 3.6</td>
<td>Summary of data associated with the feature GHa.</td>
<td>80</td>
</tr>
<tr>
<td>Table 3.7</td>
<td>Summary of data associated with the feature GHb.</td>
<td>81</td>
</tr>
<tr>
<td>Table 3.8</td>
<td>Summary of data associated with the feature GI.</td>
<td>82</td>
</tr>
<tr>
<td>Table 4.1</td>
<td>Trace length statistics.</td>
<td>105</td>
</tr>
<tr>
<td>Table 4.2</td>
<td>Spacing statistics from borehole data.</td>
<td>108</td>
</tr>
<tr>
<td>Table 4.3</td>
<td>Summary of transmissivity data for boreholes N2, N3, N4, W1, and W2.</td>
<td>113</td>
</tr>
<tr>
<td>Table 4.4</td>
<td>Distribution of fracture aperture according to orientation.</td>
<td>115</td>
</tr>
<tr>
<td>Table 4.5</td>
<td>Results from measurements of fracture surface parameters on core samples from boreholes N3, W1, and W2.</td>
<td>122</td>
</tr>
<tr>
<td>Table 5.1</td>
<td>&quot;Hit&quot; statistics for geophysical features.</td>
<td>129</td>
</tr>
<tr>
<td>Table 5.2</td>
<td>Values of correlation coefficient for comparison of hydraulic conductivity with single borehole geophysical logs and fracture frequency.</td>
<td>130</td>
</tr>
<tr>
<td>Table 6.1</td>
<td>Calculated intersections of major features with borehole C1.</td>
<td>147</td>
</tr>
<tr>
<td>Table 6.2</td>
<td>Calculated intersections of major features with borehole C2.</td>
<td>147</td>
</tr>
<tr>
<td>Table 6.3</td>
<td>Calculated intersections of major features with borehole C3.</td>
<td>147</td>
</tr>
<tr>
<td>Table 6.4</td>
<td>Calculated intersections of major features with borehole D1.</td>
<td>148</td>
</tr>
</tbody>
</table>
INTRODUCTION

1.1 BACKGROUND

Phase 3 of the Stripa Project defines a five year programme of work which was started towards the end of 1986. At the centre of this phase of the Project is a programme of work known as the Site Characterization and Validation (SCV) programme. As its name suggests, the programme focusses on the problem of validating the correctness of the techniques and approaches used in site characterization. The central aim of the programme is to predict groundwater flow in a specific volume of rock and to compare these predictions with data from field measurements. The distribution of water flow into a drift (tunnel) will be predicted, the drift will be excavated, the inflows will be measured and compared with prediction. Above and beyond the central aim there are a number of subsidiary aims such as assessment of channeling, the small scale hydrogeological effects of drift excavation and tracer tests in the fractured rock mass.

The Site Characterization and Validation programme is based around the idea of cycles of data-gathering, prediction, and validation. Hence the programme has stages of work which can be described in these terms. In fact, the programme contains two cycles of this type where predictions are checked against observation. It is therefore divided into five stages as follows:

<table>
<thead>
<tr>
<th>Stage</th>
<th>Title of stage</th>
<th>Period</th>
<th>Type of work</th>
<th>Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Preliminary site characterization</td>
<td>86-88</td>
<td>data gathering</td>
<td>first</td>
</tr>
<tr>
<td>II</td>
<td>Preliminary prediction</td>
<td>87-88</td>
<td>prediction</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Detailed characterization</td>
<td>88-89</td>
<td>validation/</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 preliminary validation</td>
<td></td>
<td>data gathering</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Detailed predictions</td>
<td>89-90</td>
<td>prediction</td>
<td>second</td>
</tr>
<tr>
<td>V</td>
<td>Detailed evaluation</td>
<td>90-91</td>
<td>validation</td>
<td></td>
</tr>
</tbody>
</table>

As can be seen Stage III fulfills two functions, that is the data gathered at this point in the programme will be compared against the preliminary predictions presented in this report. They will also provide a basis for the detailed prediction in Stage IV. (For details see "Program for the Stripa Project Phase 3, 1986-1991" (Stripa Project, 1987).
The whole programme is an attempt to carry out a detailed characterization of a volume of rock adjacent to an underground opening: a mine in this case. It is thus not meant to be compared to a site investigation programme which concerns itself with much larger volumes of rock. Some of the methods are directly applicable to a site investigation but the time scale and the detail of the SCV programme are not relevant to a preliminary site investigation.

The project aims at characterizing in detail a volume of rock which is about 125 m by 125 m in plan and about 50 m deep. The study site is situated around 380 m below ground to the north of the existing study sites and the mined-out region of the Stripa Mine (see Figure 1.1). Although the volume to be investigated is comparatively small, it will eventually consist of a small region of well-characterized rock surrounded by a larger volume of rock which is less well known. This larger volume will probably have dimensions on the order of half a kilometre.

Modelling of groundwater flow in fractured rocks has recently shifted from an equivalent porous medium concept towards a more realistic idea involving flow in networks of fractures. Although both models require input data which describe the system in terms of probability distributions the network approach requires more fundamental data (i.e. fracture geometries and properties, etc. rather than gross conductivities and porosities). The programme was prompted by this change to examine whether it was possible to gather the necessary stochastic data and whether it yielded a verifiable set of predictions. This stochastic approach requires a concurrent deterministic approach based on the assumption that some features are sufficiently large (and continuous) to be inserted specifically into the model of groundwater flow (and hence solute transport). This requires the programme of measurement to be on a scale large enough to define the "important" features in sufficient detail and at the same time yield a probabilistic data set for the rest of the rock and fracture system.

The programme of work contains a number of different techniques falling within the disciplines of structural geology, geology, geophysics, chemistry hydrogeology, and modelling. These have been combined so that predictions can be made and subsequently validated. The "cycles" of the programme envisage two modelling periods in which predictions would be made. These two periods are very different. In the first (Stage II), a conceptual model is envisaged which is
essentially geometrical with preliminary values of the important properties. Modelling at this stage will make primarily geometrical predictions. In the second (Stage IV), modelling will include the detailed properties and will include predictions of inflows to the test drift.
Figure 1.1  Location of the SCV-site relative to previous experimental areas and the mined-out cavity. Solid: 360 m level, dashed: 335 m level.
1.2 PREVIOUS WORK

The Stripa Project has been running for about a decade. The research activities at Stripa started with the Swedish American Co-operation (SAC) Project in 1977. This project was followed by Phase 1 and Phase 2 of the International Stripa Project. During this time a number of programmes of investigation have yielded measurements which are relevant to the SCV Project. They are:

<table>
<thead>
<tr>
<th>Phase</th>
<th>General title of work</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC</td>
<td>Fracture hydrology programme</td>
</tr>
<tr>
<td>1</td>
<td>Hydrogeology and hydrochemistry</td>
</tr>
<tr>
<td></td>
<td>2D Migration experiment</td>
</tr>
<tr>
<td>2</td>
<td>Crosshole Project</td>
</tr>
<tr>
<td></td>
<td>3D Migration Experiment</td>
</tr>
</tbody>
</table>

Results from the Phase 1 and Phase 2 work are published in the Stripa Project series of reports listed in an attachment at the end of this report. The SAC work is presented in a separate report series.

1.3 THE CONCEPTUAL MODEL

The purpose of this preliminary prediction report is to compile and integrate the assorted measurements made in Stage I into a coherent description of the site which can be used as a basis of flow and transport modelling, i.e. a conceptual model. It is essentially a description of the geometry of the features but the choice of which observed features to include or exclude is based on judgments concerning their flow properties. Constructing the conceptual model is a process of iteration involving data of three basic types:

- direct observation of geology and fractures along boreholes and drifts
- measurements of physical and hydraulic properties along the boreholes
- remotely sensed measurements of the physical properties of the rock between the boreholes (from radar and seismics)

The conceptual model is based first on geological observations some of which have been made on a regional scale. In the case of the SCV site all the rock is a fairly homogeneous granite so there is little structure inferred from the rock type. However, the granite is old and a complex tectonic
history determines the occurrence of joints and fracture zones. The joints and fracture zones are the main components in the conceptual model. They are observed to some extent in the boreholes, major zones are clearly visible in drifts and they are the main features visible on the geophysical remote sensing images. The division of the work into major features, identified specifically, and average rock described by probability distributions is to some extent arbitrary. However it is implicit that the major features should be selected in order that, collectively, they account for the overwhelming bulk of flow in a regional sense. Hence their "extensiveness" is a major factor controlling their selection.

The basic geometry of the conceptual model is dependant on the identification of the major features. The major features are largely identified by radar and seismic "between-hole" measurements. This is corroborated by mapping in the drifts and to a lesser extent core logging. The average rock is defined in terms of the fractures it contains. In other words the measurements of the size of fractures (areal extent), their frequency, and their orientation define the average rock. (When these data are combined with the flow or solute transport properties of the fractures it defines the flow and solute transport properties of the rock.) These measurements of the fractures are performed primarily in the drifts, using a scanline approach, and to some extent on oriented fractures in the drill core.

The intention is to define the conceptual model of the site on the basis of a first round of measurements. If the, essentially geometrical, predictions which can be made on the basis of this conceptual model are verified by the excavation and drilling in the next round of measurements (Stage III), then the geometry of the conceptual model will be used unaltered for flow prediction in Stage IV (the second round of predictions). If, as more likely, the geometrical predictions do not entirely match the Stage III measurements then the geometry of the conceptual model will be amended. These predictions will take the form of predictions of the orientation, frequency, and sizes of fractures to be encountered by the new drifts and boreholes. Also the predicted position of interaction of the major fracture zones will be checked against their actual position. In this way the confidence will be gradually improved that we know the form of fracturing to be found at the site. These predictions are given in Chapter 6 of this report.
1.4 LAYOUT OF THE REPORT

This report is a compilation and integration of the data which have been gathered during Stage I of the SCV Project. Since the SCV Project covers a wide spectrum of different types of measurements by different organizations, each task is reported separately. The relevant reports are listed below:

Site Characterization and Validation - Geophysical single hole logging by B. Fridh, Swedish Geological Co. IR 87-17.

Site Characterization and Validation - Drift and borehole fracture data, Stage I by J. Gale, Fracflow Inc. and A. Stråhle, Swedish Geological Co. IR 88-10.


Site Characterization and Validation - Stage I joint characterization and Stage II preliminary prediction using small core samples by G. Vik and N. Barton, NGI. IR 88-08.

Site Characterization and Validation - Borehole radar investigations by O. Olsson, J. Eriksson, L. Falk, and E. Sandberg, Swedish Geological Co. TR 88-03.


Site Characterization and Validation - Single borehole hydraulic testing by D. C. Holmes, BGS. IR 85-04.

Site Characterization and Validation - Hydrochemical investigations by P. Wikberg, M. Laaksoharju, A. Sandino, and J. Bruno, KTH. IR 89-09.

In order to devise a conceptual model it is necessary to take information from all these sources. This report is meant to summarise the measurements which have been made and to show how these have been interpreted to form the conceptual model. The predictions based on the conceptual model are given in terms of what is expected to be found and measured in the access drifts and boreholes constructed in Stage III.
THE SITE OF THE SCV PROJECT

2.1 GEOLOGY

This section is a summary of results from previous geological investigations in the Stripa area. Data are mainly from Olkiewicz, Gale, Thorpe, and Paulsson, 1979, Wollenberg, Flexer, and Andersson, 1980, Lundström, 1983, and Carlsten, 1985.

2.1.1 Regional geology

The bedrock in the Stripa area is mainly composed of metamorphic rocks, volcanics, and acid intrusive rocks of granitic composition. Various volcanic and sedimentary rocks were deposited on the pre-Svecokarelian basement more than 2000 million years ago. The leptite formation which is surrounding the Stripa granite is a metamorphic product of these supracrustal rocks. The iron ore bodies of the Stripa mine are associated with the leptites. The iron ores were formed as intercalations in acid volcanics and carbonate rocks.

During an early phase of the Svecokarelian evolution, about 1850-1950 Ma ago, the supracrustal rocks were folded and magmas intruded, which gave rise to synorogenic plutons. These plutons are not found in the immediate vicinity of Stripa but can be found about 8 km east of Stripa.

The synorogenic plutons and the supracrustal rocks were deformed in the main serorogenic phase of the Svecokarelian orogeny, about 1800 Ma ago. The serorogenic phase was characterized by intense folding, large scale migmatization, and generation of anatectic magmas. Part of this great volume of granitic material is considered to have risen towards the upper parts of the migmatites where they have formed massifs of undifferentiated granite accompanied by pegmatites. The Stripa granite belongs to this serorogenic generation of granites. Apart from the Stripa granite there are several serorogenic massifs in the surrounding area. The serorogenic plutonic rocks also occur as dikes up to a metre wide. The age of the Stripa granite has been
determined by potassium-argon dating to 1691±16 Ma (Wollenberg, Flexer, and Andersson, 1980).

The Stripa pluton outcrops in a suite of metamorphic rocks striking mainly in the NE-SW direction (Figure 2.1). The pluton is exposed over a relatively small area with a diameter of about 0.6 km. However, the extensive cover of glacial debris may obscure the true size and shape of the pluton at the surface. The location of the granite-leptite contact is known only to the south where it is observed in the mine workings of the Stripa mine. Contacts to the north, west, and east are concealed at the surface and unexplored at depth.

The Stripa granite is generally unfoliated due to the relatively mild tectonism since the intrusion. The leptite is a strongly metamorphosed sedimentary rock, normally of volcanic origin and it is the dominant rock type in the supracrustal formation. Scarce outcrops to the north and northwest of the Stripa mine indicate that the lower part of the leptite sequence, dominated by metavolcanics, forms a nearly north striking antiform structure bordered to the west and southeast by stratigraphically younger mica schists. Details of the geology in the vicinity of the Stripa mine are shown in Figure 2.2 and a vertical section through the Stripa area in the direction northwest-southeast is shown in Figure 2.3.

2.1.2 The Stripa granite

The Stripa granite is a grey, fine to medium grained, relatively uraniferous granitic rock. It shows abundant fracturing and deformation on both a microscopic scale and a megascopic scale.

A study of the radiogenic heat production and heat flow made by Wollenberg, Flexer, and Andersson (1980) suggests that the Stripa pluton is relatively small. In spite its high content of radioactive minerals (approximately 30 ppm U and 30 ppm Th) the pluton has a small influence on the regional heat flow. If it is assumed to be part of a layered structure, heat flow calculations show that it is probably not more than 1.5 km thick. Drillings made during phase 1 of the Stripa Project show that the Stripa granite is at least 1.2 km deep (Figure 2.3 and Carlsson and Olsson, 1985).

The granitic matrix is composed mainly of quartz (=35%), plagioclase (=30%), microcline (=25%), and to a lesser extent muscovite (=5%) and chlorite (=4%, which is a alteration product from biotite).
Accessory opaque minerals are garnet and zircon. Oligoclase is the probable species of plagioclase present in the Stripa granite. Plagioclase is generally altered to sericite. Microcline is commonly perthitic or microperthitic, with alteration similar to, but much less intense than that in plagioclase. Quartz is unaltered, clean, and grains are commonly intergrown in a sutured texture. Hematite is occasionally dispersed as fine dust and is responsible for the red colour. Muscovite occurs clear and unaltered as well as partially altered to chlorite and sericite. Biotite is commonly altered to dark green chlorite, with occasional brown biotite remnants. Garnet, possibly spessartine-almandine (Mn+Fe), is a common accessory mineral in the Stripa granite.

Breccias, containing fragments of the granitic rock, are usually a major component in wide fractures or fracture zones. The fragments are generally up to several mm in diameter (sometimes up to several cm) and may be angular or rounded. Crystals often show kinked twin or cleavage planes and a high degree of alteration on a microscopic scale. Materials filling interstices between fragments include chlorite, sericite, epidote, carbonate, hematite and other opaque minerals, fluorite, clay, and finely comminuted quartz and feldspar grains.

In some prominent wide fractures, breccia is not the dominant filling material. Instead such fracture fillings are generally dominated by carbonate or chlorite. Chlorite often occurs alone or in a densely intergrown mosaic with quartz and sericite. Lenses rich in epidote or opaque minerals are present in some places. Pyrite may be locally abundant. Usually, wide fractures are foliated due to alignment of lenses of various materials. Foliation is also accentuated by parallel orientation of fine veins within the fracture zones. In places where breccia is a component of the fracture filling it occasionally develops the texture of mylonite gneiss.

In addition to the coarse breccias common in wide fracture zones, fine grained breccias visible only in thin sections are abundant in the Stripa granite. These have been termed "microbreccia" and consist of a tight mosaic of broken angular quartz and feldspar grains with very sparse generally chloritic interstitial fillings (Wollenberg, Flexer, and Andersson, 1980).

In the core from the boreholes, idiomorphic crystals have been found at several places and almost exclusively in association with the brecciated parts. These crystals are made of calcite and/or fluorite.
which had the possibility to grow freely and thereby to develop their characteristic crystal surfaces (Cansten, Magnusson, and Olsson, 1985).

2.1.3 Leptite and iron ore

The leptites have been interpreted as originating from rhyolitic lavas and tuffs, possibly deposited in water as indicated by a well-represented ripple structure at the 360 m level in the mine (Lundström and Norlander, 1983). The leptite is usually a grey-green to black, fine-grained, foliated metamorphic rock usually cut by fractures filled with white or light green minerals. Mineralogically it is similar to the Stripa granite. It is composed mainly of quartz, plagioclase, microcline, chloritized biotite, and muscovite. Texturally it differs from the granite as it is more even and fine-grained and homogeneous.

Mining in Stripa started as early as 1448 and has continued intermittently until 1977 when the mine was converted to a research facility. The production during the period 1950-1977 was about 300 000 metric tons of ore per annum. The iron content of the ore was about 50% and it had a very low content of phosphorus (0.007%). Over its operating lifetime the mine produced a total of about 60 million metric tons of ore. Almost all of the ore deposits occurred in the leptite formation. The ore is now almost completely excavated and large open stopes now exist in the space previously occupied by the ore.

The ore layers are stratabound with the leptite formation, and form a synform with the fold axis dipping gently towards the east-northeast. The ore is found in two layers, a "main ore" and a "parallel ore" layer. The "parallel ore" layer is parallel to the "main ore" and stratigraphically under the main ore. Above the 200 m level the southern fold limb of the "parallel ore" is missing, while both limbs are present below this level. The leptite exhibits a distinct foliation below the "main" and "parallel" ores but not above.

2.1.4 Fractures and fracture zones

The regional lineament pattern typical of the part of Sweden where Stripa is located is dominated by long north-northwest and east-west striking lineaments. These lineaments have in some areas served as supply channels for Jotnian dolerites and also probably serorogenic granites. They are regarded as tensional
fractures and formed more than 1800 Ma ago. This lineament pattern can only partly be found in the Stripa region (Figure 2.4). The north-northwest striking lineaments are not as distinct as in nearby areas and the east-west striking lineaments do not appear at all. However, the regional structure shows persistent lineaments at the surface with a north-northwesterly orientation. These persistent lineaments generally have a spacing of about 1 km or more. A subordinate system of lineaments occurs which is shorter in length and which exhibits scattered directions. This subordinate system also includes the northeast direction found in the Stripa mine.

The local bedrock structure (Figures 2.1 and 2.4) around Stripa is dominated by a northeast-southwest trending syncline (the Guldsmedshytte syncline). Additional smaller synclines, one of which contains the Stripa ore zone, trend both parallel and perpendicular to the major southwest trending syncline and add to the overall structural complexity of the region. Superimposed on the regional fold pattern is a series of fracture zones and lineaments with at least one major fracture zone trending perpendicular to the major Guldsmedshytte syncline that cuts across Lake Råsvalen.

The deformation phase which formed the Guldsmedshyttan syncline and associated fold structures is thought to be due to an east-west compression. The resulting fold axes are mainly horizontal with a roughly north-south trend and have been observed at Stripa. The deformation phase which gave rise to the Guldsmedshyttan syncline and associated folds was succeeded by a second phase thought to be related to a north-south compression. This phase resulted in refolding of the sequence along east-plunging fold axes.

Fractures in the Stripa granite are partly healed and joined with the surrounding rock to form a more or less firm rock mechanical unit. Mylonites, epidote filled fractures and quartzhealed breccias are general observations especially in association with important fracture zones. Thin sections from such zones show initial crushing and mineralogical indications of late metamorphism, probably depending on fracture forming tectonic movements.

The Stripa granite is characterized by a great abundance of fractures and a variety of fracture filling minerals. Fractures ranging from well under a mm to several cm or more in width as well as wider zones of brecciation are readily visible in hand samples. The great majority of fractures have been
sealed but in some cases fine openings not visible on the macroscopic scale can be seen in thin sections.

Fracture-filling minerals have been introduced in at least two stages, the earlier stage encompassing quartz, sericite, feldspar, epidote, and chlorite, while the later stage is dominated by carbonate minerals. Numerous fractures contain fillings of brecciated parent rock.

The most common fracture filling minerals in microscopic appearance are chlorite, sericite, quartz, epidote, and carbonate minerals. Flourite and opaque minerals (usually pyrite and hematite) are somewhat less common. The thickness of fracture fillings spans over a wide range from less than 0.001 mm to centimeters. Generally only finer fractures are filled with single minerals, usually quartz, sericite, chlorite, and carbonate. Coarser fractures are almost invariably filled with intergrowths of two or more minerals, usually sericite and chlorite. Quartz occurs in combination with any of the fracture filling minerals. Epidote is usually associated with quartz, chlorite, or sericite as is carbonate which is sometimes intergrown with flourite as well. Flourite is usually intergrown with quartz, carbonate, chlorite, or rarely with epidote. Pyrite is sometimes intergrown with sericite and chlorite.

A few major fracture zones or dislocations have been observed during the previous investigations in the Stripa mine. There is a dislocation of the ore body with a relative displacement of about 20 m which is observed at the 410 and 385 m levels of the mine. This zone strikes northeast and dips about 75° to northwest (Olkiewicz, Hansson, Almen, and Gidlund, 1978). The zone continues from the ore in a northeasterly direction where it is observed in the Crosshole site and was labelled zone C (Olsson, Black, Cosma, and Pihl, 1987 and Figure 2.2). Three other zones which were classified as major were identified at the Crosshole site. These zones are steeply dipping and strike north-northeast or northeast.

A major zone of unknown orientation was intersected at a borehole length of 480-505 m in borehole V1, measured from the 360 m level. This zone produced a large outflow (=7 l/min) of saline groundwater.
Figure 2.1  Regional geology of the area around Stripa (from Lundström, 1983).
Figure 2.2 Detailed geology of the immediate area around the Stripa mine.
cross section of mine layout and geology

Figure 2.3 Vertical geologic section through the Stripa mine. The location of the profile is shown in Figure 2.2.
Figure 2.4 Major structural features in the Strömpa area on a regional scale (from Lundström, 1983).
2.2 LAYOUT

The site for the Site Characterization and Validation (SCV) program was selected on the criteria that it should provide a previously unexplored volume of granite with a size of about (125 m x 125 m x 50 m). A suitable site was found west of the 3D-migration drift.

The SCV-site is located about 100 m north of the old mine workings (except for the 3D-migration drift) between the 360 and 410 m levels. The selected location made it possible to explore the rock volume through boreholes made from existing drifts.

The location of the existing mine workings in relation to the site is important as they provide hydraulic boundaries of atmospheric pressure. All mine workings above the 435 m level are open and air filled. Figure 2.5 shows the location of the site in relation to the ore body and old mine workings.

Figure 2.6 shows the location of the SCV-site and its boreholes in a plan view. Five "boundary boreholes" have been drilled for preliminary characterization of the site: three holes towards the North (N2 - N4) of 200 m length and 60 m apart, and two towards the West (W1 - W2). These holes of 150 m length are roughly 70 m apart. A 50 meter long vertical hole (V3) has been drilled at the end of the 3D-migration drift mainly for the purpose of measuring rock stresses. In Table 2.1, the position of the boreholes in the local mine coordinates, bearing (from mine north), plunge (from horizontal plane), and length are given. The total length of the holes drilled within Stage I is 960 m. The holes are 76 mm in diameter and fully cored.

The following criteria were used to determine the location of the "boundary boreholes":

- maximum coverage of the rock volume was aimed at in relation to the drilled length of borehole. Coverage should be obtained both horizontally and vertically.

- the site should be penetrated by boreholes in at least two different directions.

- the geophysical methods were considered to give acceptable resolving power only if the distance between the boreholes was limited to 75 m.

- the drilled borehole length should be minimized through drilling from existing mine excavations.
the boreholes should be directed downwards to have them filled with water (a prerequisite for hydraulic testing).

Figure 2.6 also shows the location of a number of old boreholes which exist in the vicinity of the SCV-site. SBH1 starts at the ground surface east of the 3D-migration drift and extends down towards the BMT-area. The borehole is well above the SCV-site and it ends at a vertical depth of 285 m. In this hole the leptite extends down to a borehole depth of about 205 m which corresponds to a vertical depth of about 140 m. Borehole SBH3 also starts at the surface, it is 315 m long and ends at a vertical depth of 260 m. The rock type along the entire length of this hole is granite. The plunge of SBH1 and SBH3 is 46 and 49 degrees, respectively. Borehole Bh 96 is drilled from the 310 m level and extends almost horizontally eastwards.

The HG- and R-holes are all about 30 m long and drilled from the BMT-drift (or Ventilation experiment drift). These holes were all drilled as a part of the SAC-programme. There is also a 100 m long borehole, P1, extending northwards with an upward plunge of 7° drilled from the 360 m level. Borehole N1 is located about 50 m east of the 3D-migration drift and is directed towards north. The plunge of N1 is 8° down.

Not shown on the map are three vertical boreholes, each 70 m long, extending vertically upwards from the 3D-migration drift. These holes (II, I2, and I3) were used for the injection of tracers during phase 2 of the Stripa Project (Abelin and Birgersson, 1988).

Packers have been installed in the R and I boreholes, P1, and N1. The sealed off borehole sections have been connected to a computerized head monitoring system (Piezomac) which has been in operation since December 1986 (Carlsten, Olsson, Persson, and Sehlstedt, 1988).

A block has been selected for investigation within the SCV-project. The block is a cube with sides 150 m in length which is somewhat larger than the dimensions indicated in the programme plan. The increase in size has been motivated by the need to define appropriate boundary conditions. However, detailed information on the properties of the block will only be collected in the centre of block. This implies that reasonable predictions of conditions can only be made in this part. The coordinates for the eight corners of the cube are listed in Table 2.2.
Table 2.1

Position of boreholes W1, W2, N2 - N4, and V3, in the local mine coordinates. Bearing from mine north (in degrees), plunge below horizontal plane (in degrees), length (m), together with date for start and completion of drilling.

<table>
<thead>
<tr>
<th></th>
<th>W1</th>
<th>W2</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>V3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collar position:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>440.0</td>
<td>510.0</td>
<td>333.3</td>
<td>347.4</td>
<td>321.1</td>
<td>502.9</td>
</tr>
<tr>
<td>Y</td>
<td>1146.8</td>
<td>1147.4</td>
<td>1139.2</td>
<td>1079.1</td>
<td>1023.1</td>
<td>1149.7</td>
</tr>
<tr>
<td>Z</td>
<td>356.1</td>
<td>355.3</td>
<td>356.7</td>
<td>356.9</td>
<td>345.0</td>
<td>356.5</td>
</tr>
<tr>
<td>Bottom hole position:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>441.7</td>
<td>511.4</td>
<td>530.1</td>
<td>527.4</td>
<td>529.0</td>
<td>503.4</td>
</tr>
<tr>
<td>Y</td>
<td>1000.3</td>
<td>1000.8</td>
<td>1141.0</td>
<td>1082.6</td>
<td>1025.5</td>
<td>1149.7</td>
</tr>
<tr>
<td>Z</td>
<td>368.1</td>
<td>365.9</td>
<td>420.7</td>
<td>414.2</td>
<td>413.7</td>
<td>404.5</td>
</tr>
<tr>
<td>Collar direction:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearing</td>
<td>269.94</td>
<td>269.90</td>
<td>359.85</td>
<td>359.97</td>
<td>359.25</td>
<td></td>
</tr>
<tr>
<td>Plunge</td>
<td>4.99</td>
<td>5.02</td>
<td>18.59</td>
<td>18.59</td>
<td>18.80</td>
<td>89.33</td>
</tr>
<tr>
<td>Bottom hole direction:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearing</td>
<td>271.39</td>
<td>271.19</td>
<td>0.87</td>
<td>2.20</td>
<td>2.12</td>
<td></td>
</tr>
<tr>
<td>Plunge</td>
<td>4.13</td>
<td>3.32</td>
<td>17.31</td>
<td>17.01</td>
<td>17.47</td>
<td>89.49</td>
</tr>
<tr>
<td>Length</td>
<td>147</td>
<td>147</td>
<td>207</td>
<td>189</td>
<td>219</td>
<td>50</td>
</tr>
<tr>
<td>Drillstart</td>
<td>861023</td>
<td>861105</td>
<td>861006</td>
<td>860917</td>
<td>860829</td>
<td>861201</td>
</tr>
<tr>
<td>Drillstop</td>
<td>861103</td>
<td>861120</td>
<td>861016</td>
<td>861001</td>
<td>860911</td>
<td>861204</td>
</tr>
</tbody>
</table>

Table 2.2

Coordinates of the 8 corners of the block to be modelled.

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>400</td>
<td>1000</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>1150</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>550</td>
<td>1150</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>550</td>
<td>1000</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>1000</td>
<td>460</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>1150</td>
<td>460</td>
</tr>
<tr>
<td></td>
<td>550</td>
<td>1150</td>
<td>460</td>
</tr>
<tr>
<td></td>
<td>550</td>
<td>1000</td>
<td>460</td>
</tr>
</tbody>
</table>
Figure 2.5  Perspective view of mined out area in relation to the SCV-site.
Figure 2.6 Map of the SCV-site indicating the location of the "boundary boreholes", boreholes drilled prior to the start of the SCV Project, and existing mine workings. Dashed 310 and 335 m levels, solid 360 and 410 m levels.
2.3 HYDROGEOLOGICAL SETTING

2.3.1 Importance of hydrogeological setting

The hydrogeological setting of the SCV site is extremely important to the outcome of the SCV project since the inflow of groundwater to the Validation Drift is the major form of "validation" envisaged for the project. Although only a comparatively small region of the mine and its environs will be measured and modelled in detail it is nevertheless necessary to consider the form and direction of regional groundwater flow. This is because the presence of extensive hydrogeological features of considerable transmissivity within a low flow environment can spread the effect of the changing groundwater conditions in the SCV area over a wide area (and vice versa). Similarly the mine acts as a sink for the local (and regional) flow field and hence groundwaters of widely differing chemistry could potentially arrive within the SCV area. With sufficient knowledge of the regional flow it should be possible to use much of the groundwater chemistry data to validate or modify concepts of flow within the SCV area. The final aspect of the regional hydrogeology relevant to the SCV experiment is the use of the regional flow modelling to define the boundary head conditions around the region modelled in great detail in the last phase of the SCV Project.

2.3.2 Regional flow

The direction and magnitude of regional groundwater flow is largely determined by the topography of the water table and the configuration of regions of high and low hydraulic conductivity. In the region of the Stripa Mine the groundwater flows from the high relief in the north and west of the mine towards Lake Råsvalen south east of the mine (see Figure 2.7). The mine is the deepest sink in the region and has now been open for so long that some of the regional flow towards Lake Råsvalen is now intercepted by the mine. There is the added possibility that some water has actually reversed its direction of flow in response to the presence of the Stripa mine. These effects, amongst others, have been examined using a numerical model by Gale and others (1987).

The modelling consisted of using a 3-D, finite element, coupled fluid energy and solute transport model (CFEST) at two scales: regional and sub-regional (see Figures 2.8 and 2.9). The elements were
irregular and the rock was treated as an equivalent porous medium, albeit with variable properties according to rock type and depth. The regional model was assumed to have "no-flow" basal and side boundaries and a known head along the top surface. The code then calculated the head and flow distribution within the region based on known (or assumed) values of hydraulic conductivity. The model was constructed to include lithological variations and fault zones.

The sub-region model was a more detailed model of the mine area within the regional model and used the heads determined in the regional model as boundaries. The geology was treated in more detail and mine inflow was calculated. A case where the rock and the fracture zones were assumed to have depth-dependent hydraulic conductivity was found to yield reasonable values of inflow to the mine compared to those measured.

The results indicate that part of the groundwater discharging into the mine recharged at a considerable distance to the north and west (in some cases almost 10 kms away). Flow lines also indicate that the water entering the mine may have reached considerable depth before turning upwards to flow into the mine. The models also showed that groundwater may now be flowing towards the mine from Lake Råsvalen and in this case some of the water would have reversed direction in response to the dewatering of the mine over the last 100 years. Using the models to calculate flow lines shows the influence of the major regional fracture zones in defining the flow routes towards the mine. Additionally the flow paths are highly individual as they appear (in plan) to cross each others paths, albeit with considerable vertical separation.

Hence the modelling of the mine within the regional flow system indicates that the regional flow system includes a large region and that the mine is a major sink within that region. Its effects are therefore seen at large distances from the mine and the presence of the fracture zones ensures that flow directions are extremely variable on a local scale. Thus the interaction of the mine with the regional flow system determines the flow boundary conditions in the immediate mine area.
Figure 2.7 Map of regional water table around the Stripa Mine with approximate directions of groundwater flow.
Figure 2.8 Finite element mesh and simplified geology for the regional model showing the location of the major lakes and fracture zones (heavy black lines).
Figure 2.9 Finite element mesh and simplified bedrock geology for the sub-region model showing the mine tailings pond, Lake Råsvalen, fracture zones (heavy black lines), and the Stripa mine ventilation shaft.
2.3.3 Hydrochemistry and regional flow

There has been extensive sampling of the groundwater for the purposes of chemical and isotopic interpretation of the movement of the groundwater. Data have been gathered since 1978 and were recently summarised by Gale and others (1987).

The regional groundwater flow modelling provides a basic framework for an assessment of the current flow of groundwater towards the mine opening. The layout of the mine openings and the location of the SCV site relative to the geology of the area are shown in Figure 2.3. In particular the relation of the SCV site to the mine openings can be seen, indicating how the site lies across the converging flows to the cavity (see Figure 2.10). The regional flow model which best imitated the measured mine water inflows used a depth dependent relationship. This means that under a constant hydraulic gradient, flow rates (and speeds, if porosity is reasonably depth independent) will be considerably more rapid near the surface.

The residence times along the flow lines from the surface to the mined opening will vary from zero to a few hundred years. In contrast the residence time of groundwater upwelling from below might range from 3000 to 4000 years within a similar distance along the incoming flow lines. What this means in practice is that samples of groundwater from the boreholes beneath the mine should be relatively old and not change rapidly with time. On the other hand samples from boreholes intersecting the direct flow routes from the surface should yield highly variable waters. There will also be a region where considerable mixing will occur. If the data from the previous investigations are treated in a general way (i.e. averaging samples from equal depths) then mixing seems most prevalent between 200 m and 350 m below ground.

Thus one can divide the waters into two types which have been mixed to varying degrees in the region of the SCV site. The "direct surface" water has a chloride concentration less than 100 mg/l whilst the "deep" water has a concentration exceeding 500 mg/l. Since the rock types vary along the potential flow paths many of the dissolved species resulting from water-rock interaction show no large scale consistent trends. However, there are some interesting aspects of the data on tritium when examining series of samples taken from horizontal boreholes at the same depth. For instance samples from the boreholes E1 and F2 from the Crosshole site indicate "modern" water whereas samples from borehole N1 (and V1) show no "modern" water. Boreholes E1 and F2 both head towards
a drift which acts as a sink whereas the other two are directed away from the mine excavations.

Taken overall the hydrochemistry and isotope data indicate that the SCV site is in a region of mixing. Groundwaters upwelling from below should be of relatively constant composition. Groundwaters draining from above will be highly variable. The immediate environs of the mine cavity are characterised by modern directly draining groundwaters. Features such as fracture zones or boreholes which connect the surface waters and the mine cavity will contain anomalously "young" waters. It is likely that the surface boreholes SBH1, SBH2, SBH3 and SBH4 are altering the composition of the groundwaters surrounding their lower regions.

Figure 2.10 Postulated flow in region with hydrochemical implications (cf. the geological cross section of the mine shown in Figure 2.3).
2.4 STRESS FIELD

The in-situ stress field around the Stripa mine has been measured at a number of points using several different techniques (see Doe and others, 1983, and Strindell and Andersson, 1981, Bjarnasson and Raillard, 1987). These measurements have been distributed around the northern end of the mine approximately surrounding the SCV site (see Figure 2.11). There is some variation in the orientation of the observed principal stress. At the depths involved in the Stripa mine (i.e. less than 500 m) the minimum natural undisturbed stress is the vertical component. In SBH4, to the north of the site, the maximum horizontal stress as measured is oriented approximately NW-SE. From modelling work (2D in plan and section) performed by Chan and others (1981) it was calculated that measurements in SBH4 should not be affected by the mine cavity and that they therefore represented the "undisturbed" stress field. Measurements in the SAC area showed a different orientation with the principal stress direction rotated through about 45 degrees. However there is considerable scatter in the results based on overcoring. In the most recent phase of the Stripa project a new set of results has been gained from a vertical borehole (V3) at the end of the 3D drift. There is reasonable agreement between the stress orientations measured at V3 and the so-called undisturbed results from SBH4.

The stress measurements in V3 gave a value of 11.1 MPa for the minimum horizontal stress while the maximum horizontal stress was found to be approximately twice as large (Bjarnasson and Raillard, 1987). The vertical stress was found to be equal to the lithostatic stress from the weight of the overburden (9.2 MPa at 380 m).

The modelling work of Chan and others (1981) suggests that this is what would be expected around an opening as large as the mined out cavity. Stress redistribution effects decrease approximately logarithmically with distance from a cavity whilst the magnitude of the effect is proportional to the cavity's minimum dimension. This effectively means that the natural stress field will be disturbed predominantly by the mined out cavity and that location relative to the cavity is the major influence on stress alignment. The results of the modelling of Chan and others, 1981 have been replotted around the SCV site (see Figure 2.12) and indicate that the stress field can be expected to be realigned marginally in the area. There is some distortion with the modelling of Chan and others
(1981) when it is applied at this scale (i.e. the position of the mined out cavity has been transposed about 100 m to the west for the purpose of simplifying the modelling).

A second explanation has been put forward (Chan and others, 1981) for the measured distribution of stress based on the idea of a natural variation in the orientation of the stress field associated with tectonic history and the complex mechanical properties of the ore body. Given the reasonably homogeneous lithology of the SCV site and the agreement of the measurements with the modelling of Chan and others, 1981, the stress relief concept seems sufficient to explain the stress situation. However it should be borne in mind that there is some expected variation of stress along the lengths of the boreholes N2, N3 and N4.
Figure 2.11  Summary of the stress measurements performed in the Stripa mine (1977-1988).
Figure 2.12 Calculated principal stress distribution at the 360 m level in the vicinity of the SCV site (from Chan and others, 1981).
3 MAJOR STRUCTURAL FEATURES

3.1 IDENTIFICATION OF MAJOR FEATURES

3.1.1 Introduction

A basic assumption underlying the description of groundwater flow and nuclide transport through crystalline rock is that flow and transport take place in fractures. In a description of groundwater flow through rock we cannot expect to find every single fracture and describe its geometry and properties. Hence, the fractures which cannot be identified on an individual basis have to be described statistically or by some form of averaging. However, we know that fracture zones exist and that they in many cases are preferential groundwater transport paths. Knowledge about the location and properties of fracture zones can often be obtained and should then be included in the groundwater flow and transport model as specific (deterministic) features.

An important issue in this context is to have a strict definition of what is a fracture zone and what is regularly fractured rock. The concept of a "fracture zone" normally leads to a number of imprecise connotations as the concept of fracture zones generally depends on the purpose of a specific study. To avoid this we have for this project defined the concept "major feature" which has a geometric definition.

The basic criteria for a "major feature" is extent, i.e. the definition is geometrical. There is a certain rationale in the search for and identification of extensive features, from the groundwater transport point of view, in that extensive features are the ones most likely to provide fast transport paths and hence control the bulk of the water flow through a specific volume of rock. In order to classify a feature as extensive it needs to be observable for a length on the order of the dimensions of the investigated site (in this case 50-100 m). This makes extent a relative measure depending on the size of the investigated volume. Normally data density, and hence resolution, is also a function of the size of the investigated volume.
In order to include a major feature in a model we should be confident about its location. In practice this implies that the detection of major features depends on the investigation methods applied and the density of measuring points.

The characterization of the SCV-site has been made from the 5 "boundary" boreholes and to a minor extent from adjacent drifts. Most of the single hole investigation methods (geological, geophysical, and hydrological) have a very small radius of investigation (<1 m) and hence they provide data on the rock properties only at points along the lines made up by the boreholes. This type of data makes it difficult to draw conclusions about the extent of intercepted features. Even if single hole data of this type can be used to some extent to deduce extensiveness it is difficult to make reliable judgments on the orientation of features due to the large distance between observation points. The distance between the "boundary" boreholes is on the order of 50 m.

Of the methods employed in the SCV Project the radar and the seismic methods are the only ones which really give information on the extent and location of geological features in the rock mass. They are true remote sensing methods in the sense that they provide high resolution data (on the order of metres) at large distances from the boreholes. A consequence is that the structures in the rock mass which we define as "major features" are geophysical features based on data from radar and seismic measurements. Identification of features is hence based on extent and anomalous electric and elastic properties. This does not necessarily imply that the features have hydrological significance even though this is often the case. An example is given by the results from the investigations at the Crosshole site which showed that the important hydrologic features were a subset of the geophysically defined features and very little flow occurred in the rock mass outside the geophysically defined zones (Olsson, Black, Cosma, and Pihl, 1987).

The investigations at the Crosshole site did not result in a quantitative relationship between electric and seismic anomalies and hydraulic properties. This implies that the magnitude of geophysical anomalies can not be taken directly as a measure of hydraulic properties. Instead the geophysical features should initially be considered as potential hydraulic pathways and hence geometric constraints on the hydrologic model. Data on the hydraulic properties of the features have to be
obtained through single hole and crosshole hydraulic tests. The geophysically defined zones should be retained in the conceptual model if they are found to be hydraulically significant. It should also be recognized that the geometry of flow paths cannot be deduced from hydraulic tests with any accuracy and that a certain flow geometry is actually assumed for the derivation of hydraulic parameters from hydraulic tests.

As mentioned above, a model of major features is defined based on the results from the radar and seismic measurement. This model is checked with the single hole data which also contain indications of extensiveness of intercepted features. For example, geological evidence of faulting in the core such as brecciation, mylonitization, alteration, and red colouring are considered as such indications. Alteration and red colouring indicate that there has been water flow in these features in geological time. Geological evidence of faulting is normally associated with anomalies on several single hole geophysical logs.

This chapter will present results from the radar and seismic investigations and correlate those results to the observations made in the boreholes. The integrated analysis of the data from the SCV-site is presented in the last two sections of this chapter.

3.1.2 Radar technique

The borehole radar technique uses electromagnetic waves concentrated in a short pulse with a length in the rock of 2-10 m to obtain information about the structure of the rock. Radar wave propagation is sensitive to the electric properties of the rock, mainly the dielectric constant and the electrical conductivity. The variation of these properties is related to other physical properties of the rock which are of more direct interest to groundwater flow, such as porosity and fracturing. An essential aspect of the borehole radar method is that it combines resolution on the order of meters with investigation ranges on the order of hundreds of meters. This means that detailed information can be obtained on structures located far from the boreholes. In some sense the radar gives the ability to "see" through the rock.

The borehole radar investigations made during Stage I of the SCV Project have comprised the following items (Olsson, Eriksson, Falk, and Sandberg, 1988);
Single hole reflection measurements have been made in the 6 boreholes at two different frequencies. A low frequency (22 MHz) has been used to identify the large scale features at distances of up to 100 m from the boreholes and a high frequency (45 and 60 MHz) to identify smaller features closer to the boreholes.

Crosshole reflection measurements have been made between 5 pairs of boreholes at frequencies of 22 and 60 MHz. The total number of crosshole reflection scans is 42. (A borehole scan is a set of measurements where one probe (transmitter or receiver) is kept fixed in one borehole while the other probe is moved in another borehole where measurements are made at fixed increments. The increment is normally 1 m in crosshole reflection measurements.)

Crosshole tomographic measurements have been made in the planes spanned by the boreholes at frequencies of 22 and 60 MHz. The measurement program has included a total of 7 borehole sections. Tomographic inversion has been made of both travel time and amplitude data.

The radar measurement program at the SCV-site totalled over 20 000 rays which corresponds to approximately 10 million data values.

From each measurement mode the following information has been extracted from the processed radar data:

- The grey scale radar maps from single hole reflection measurements have provided data on where features intersect the boreholes (or their linear extension) and the angle with which the structures intersect the boreholes. An example of a single hole reflection result is shown in Figure 3.1. In this figure the dominant reflector is the 3D-migration drift and its access drift. Two reflectors nearly parallel to the boreholes are clearly visible at distances of about 30 m (feature RH) and 50-60 m. A number of features intersecting the hole at steeper angles are also indicated.

- The crosshole reflection grey scale radar maps have given data on where features intersect the boreholes (or their extension) and a value of a quantity called "slope" which gives a constraint on the possible orientations of the feature.

- The tomography surveys have provided a description of the features in the plane defined by the two boreholes between which the measurements were made. From the tomographic
inversion we get a map of the variation of electric properties in the plane. This gives a possibility to study variations in the properties of the feature along its lateral extent and to study details of its geometry (undulations, faulting, etc.). In the three dimensional geometric analysis of the structures the location of the feature in the plane is used (or actually the intersection of the feature with the two boreholes).

The first step in the integrated analysis of the radar data is to identify the major features in the three data sets and to make certain that each feature is identified correctly in all three data sets and in all measured boreholes. Normally a feature is first identified in one of the tomographic maps. The intersection of the feature with two of the boreholes is then readily identified. If the feature is assumed to be planar then the definition of two points on that plane forces the normal of the plane to be perpendicular to the line connecting the two points. The possible orientations of the normal are then displayed as a line in a Wulff diagram.

When the intersection of a feature with two boreholes is known then the single hole reflection data from these boreholes are studied. Reflections can normally be found at the intersection points and the angle of intersection between the borehole and the feature gives another constraint on the possible orientation of the plane of the feature. The tomographic measurements at the SCV Site have all been performed between parallel boreholes. A consequence of this is that the angles of intersection provided by the single hole reflection data at the two intersection points are nearly the same. The curve describing the possible orientations of the normal defined by the single hole reflection data are plotted in the same Wulff diagram. The intersection of the curves obtained from the tomography data and the single hole reflection data normally define two points, i.e. there are two possible orientations. This ambiguity is a consequence of that up to this point only data collected in one plane has been considered. Due to the omnidirectionality of the radar antennas such data will always have a mirror symmetry with respect to the plane of measurement.

The next step in the analysis is then to identify the same feature in the other plane defined by the "boundary boreholes". The borehole layout at the SCV-site essentially provides us with two different planes, i.e. the plane defined by the three boreholes N2-N3-N4 and the plane defined by W1-W2.
Suitable candidate features are sought in the tomographic maps and the single hole reflection data belonging to the "other" plane. The values on borehole intersections and angles of intersections are checked with the previously obtained data and checked for consistency. Finally crosshole reflection data are also included in the analysis and checked for consistency. If all the data included in the analysis are consistent it is considered that a major feature has been identified with significant lateral extent, i.e. at least comparable to the dimensions of the site. In this case the location of the feature and its orientation can also be considered to be defined with a high degree of confidence.

During the interpretation of data sets like the borehole radar data there will be different degrees of consistency between the data sets for different features. This will of course result in that the reliability in the various aspects of the description of the zones will vary between the zones. Smaller features, which could possibly exist but only be defined with a low degree of confidence, have not been included in the description of the site. This implies that a cut-off or truncation has been introduced in the interpretation process which may not reflect the actual conditions. There may in fact be a range of length scales between the major features and the individual joints which is not completely represented in the conceptual model.

The analysis of the radar reflection data has been performed under the assumption that the reflectors (fracture zones) are essentially planar features. This assumption is of course a generalization which appears to be relevant at the scale of the site. If the features are studied in detail, we observe that the features are not exactly planar. Instead they tend to undulate somewhat and their thickness and contrast in properties with respect to the background varies along their extent. These small scale variations are particularly visible in the tomograms.

From the radar data it was possible to identify three major features and four minor features. The location of these features are indicated on the attenuation and slowness tomograms from the two planes defined by the boreholes N2-N3-N4 and W1-W2 (Figures 3.2-3.5).

The features RA, RB, and RH are considered as major while features RC, RD, RK, and RL are of smaller magnitude. The features can also be grouped according to their orientation. The features with a northeasterly strike (N40-50°E) and a dip of approximately 35° to the south are RA, RB, RC, and RD. Features RK and RL are nearly perpendicular to
this set and have a strike approximately N55°W and a
dip of 65-70°N. The feature RH strikes NNW and has a
steep dip (60°) to the east.

(The annotation of the features by Rx, indicates that
the features have been identified by the radar
method and that the interpretation is based solely on
radar data.)

The features, as they are seen from the tomograms,
consist of a number of patches of increased
attenuation and slowness that follow lines in the
planes between the boreholes. Increased slowness
and/or attenuation correspond to increased porosity,
fracturing, and/or alteration of the Stripa granite.
The results indicate that the features are not
homogeneous but rather that they are highly irregular
containing parts of considerably increased fracturing
and parts where their contrast to the background rock
is quite small. The features appear to be
approximately planar at least at the scale of the
site. If the geometry of the features are studied at
a smaller scale the planarity of the features might
be less obvious. At the smaller scale the features
appear quite irregular and in effect pinch and
swell along both strike and dip.

One of the most extraordinary features in the
attenuation tomograms is the circular feature (RQ)
between boreholes N3 and N4. The existence of the
feature and its shape must be considered to be real
and not an artifact produced by errors in the data or
the tomographic inversion procedure. The feature
appears both in the two attenuation tomograms from
the borehole section N3-N4 and in the borehole
section N2-N4. These two sections are made up of two
completely different sets of rays which are nearly
in the same plane. Even though the tomograms
originate from two different data sets the resulting
anomaly is located in the same place and has the same
shape in both tomograms. This fact can be considered
as strong evidence that the location and shape of the
feature is correctly represented in the tomograms.
However, it should be noted that the shape of the
feature may not be exactly represented in the
tomograms. For example, a rectangular object would
get rounded corners by the tomographic mapping.

The circular feature, RQ, is located between features
RA and RB. It is bounded to the northeast by the
feature RL. The location of RQ close to the
intersection of three features suggest a complex
origin of the feature related to the formation of the
three fracture zones. The feature, RQ, is also
remarkable because the circular shape is only evident
in the attenuation tomograms, while the slowness
tomograms have an anomaly in the centre of the feature. This could correspond to a region of increased fracturing and high permeability in the middle with a region of altered rock and clay minerals with low permeability surrounding it.

A detailed account of the analysis of the radar data is presented in the report by Olsson, Eriksson, Falk, and Sandberg (1988).
Figure 3.1 Radar reflection map from borehole N2 measured with a centre frequency of 22 MHz. Reflections marked RA, RB, RC, RK, and RH are caused by features (fracture zones) included in the radar model of the SCV-site. The strong curved reflection is caused by the 3D drift.
Residual attenuation tomogram (22 MHz) for the plane defined by the boreholes N2-N3-N4. The location of the major and minor features included in the radar model of the SCV-site are indicated.
Figure 3.3 Residual attenuation tomogram (22 MHz) for the plane defined by the boreholes W1-W2. The location of the major and minor features included in the radar model of the SCV-site are indicated.
Figure 3.4  Residual slowness tomogram (22 MHz) for the plane defined by the boreholes N2-N3-N4. The location of the major and minor features included in the radar model of the SCV-site are indicated.
Figure 3.5  Residual slowness tomogram (22 MHz) for the plane defined by the boreholes W1-W2. The location of the major and minor features included in the radar model of the SCV-site are indicated.
3.1.3 Seismic technique

In the seismic technique elastic waves are used to obtain information about the structure of the rock. The elastic waves are of two kinds; longitudinal compressional waves (P-waves) and transverse shear waves (S-waves). The compressional and shear wave velocities are related to the mechanical properties of the rock such as Young's modulus and the shear modulus. Increased fracturing normally causes a decrease in the seismic velocities. The frequencies used in the experiments have been in the range 1 kHz to 5 kHz corresponding to wavelengths in the range 5 to 1 m.

The seismic investigations at the SCV-site have comprised tomographic surveys of the borehole sections N2-N3, N3-N4, and W1-W2. The section W1-W2 included source points in the 3D-migration drift. In addition three crosshole reflection or VSP sections were made. In this case the source was located in the 3D-migration drift close to the beginning of boreholes W1 and W2 while the receiver was moved in 1 m increments in boreholes W1 and W2. In total about 1900 rays were recorded.

The seismic velocity tomograms for the sections N2-N3-N4 and W1-W2 are shown in Figures 3.6 and 3.7. The features identified from the seismic data are indicated in the figures. Note that the identification of the features is based also on the results from the seismic reflection sections. The features are annotated by the initial letter 'S' to indicate that they have been identified from seismic data. The second letter is in the cases where the seismic interpretation agrees with the radar interpretation identical to the one given in the previous section.

Figure 3.8 shows the processed result from a seismic reflection measurement. The source was located in the drift at the start of borehole W2 while the receiver was moved in W1. This configuration corresponds to what in normal seismic terminology goes under the name offset VSP. The reflection profile enhances edges of features and the profile therefore looks more like a superposition of trends rather than a collection of separate reflection events. An analysis of the reflection trends has made it possible to identify three major groups of reflectors with different orientation relative to the boreholes. The data from the three reflection sections have been combined and analyzed with the Wulff projection technique to find the orientation of each set. The
orientation data for each set are listed in Table 3.1.

Table 3.1 Main orientations of features crossing the SCV site inferred from seismic reflection analysis.

<table>
<thead>
<tr>
<th>Set No.</th>
<th>Mean dip</th>
<th>Mean strike</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35 S</td>
<td>N 45 E</td>
</tr>
<tr>
<td>2</td>
<td>60 E</td>
<td>N 350 E</td>
</tr>
<tr>
<td>3</td>
<td>60 N</td>
<td>N 305 E</td>
</tr>
</tbody>
</table>
Figure 3.6  Seismic velocity tomogram for the plane defined by the boreholes N2-N3-N4. Major features are indicated in solid lines while minor features are dashed.
Figure 3.7 Seismic velocity tomogram for the plane defined by the boreholes W1-W2. Major features are indicated in solid lines while minor features are dashed.
Figure 3.8  Processed seismic reflection profile with source in the drift at the start of borehole W2. Receiver is moved in W1. The features are seen as trends rather than as isolated events.
3.2 SINGLE BOREHOLE RESULTS

3.2.1 Evidence of fracture zones in the drillcore

In most rock types, shear and fracture zones are recognized by one or more characteristics that include clay gouge, alteration of the rock matrix by either hydrothermal fluids or groundwaters, closely spaced fracturing or specific mineral assemblages such as epidote, chlorite, quartz veins. Direct observations of the major features cutting the rock units in the Stripa mine suggest that the major features are primarily fracture zones that consist of closely spaced fractures with minor thicknesses of crushed material or fracture filling minerals. While these fracture zones show considerable offset, and hence shear displacement, they do not exhibit the clay gouge that one normally associates with shear zones. However, as indicated in Chapter 2, in the Stripa granite these fracture zones are characterized by a red stain or colouring of the normally grey granite.

The variation in fracture frequency along each borehole is shown in Figure 3.9-3.13. These figures show the number of open fractures in 1 m intervals. Small sections of crushed core have been identified in the cores and for these sections it has not been possible to count the number of fractures. Crushed core is normally an indication of fracture zones (crushed core can also be caused by the drilling process). In order to account for the crushed sections of core in the fracture frequency logs the fracture frequency has been set to 50 fractures per metre in these sections. Sections of crushed core are normally the cause for the very high fracture frequencies observed (>20 fractures/m). The effect of arbitrarily setting the fracture frequency to 50 fractures/m for sections of crushed core is demonstrated by a comparison of Figures 3.9-3.13 with Figures 4.2 and 4.3 which are based on the actually observed fractures.

In the SCV Project the boreholes were drilled using a double tube core barrel. The design of this core barrel allows the drilling fluid to wash out any fine grained, crushed, but uncemented, material that might be present in the fracture planes that make up a fracture zone. Hence, the primary evidence that would suggest the intersection of a fracture zone by the boreholes is closely spaced fracturing, red staining or colouring and rock alteration that can result in core loss by crushing and grinding. If we assume that at least two of these characteristics must be present
in the core to define a fracture zone, we find zones defined by both closely spaced fracturing and red staining or colouring at 28.6-32.0 m, 150.3-156.50 m, 158.7-162.4 m, and 182.1-207.1 m in N2; 136.7-142.9 m and 161.1-192.0 m in N3; 130-155.0 m in N4; 42.3-67.5 m and 98.0-110.5 m in W1; and 53.0-67.0 m and 126.0-129.5 m in W2.

3.2.2 Geophysical logging evidence

To achieve a comprehensive knowledge of the physical conditions in the rock mass in the vicinity of the boreholes the following geophysical borehole methods have been used: borehole deviation, natural gamma ray, neutron - neutron, sonic, single point resistance, normal resistivity, temperature, borehole fluid resistivity (salinity), and televiewer.

The porosity of the bedrock has been calculated using the resistivity measurements. The porosity values fall in the range 0.3% to 1.5 % with the highest values in the deeper parts of W2. Boreholes N2, N3, and V3 generally have low porosity values.

In each of the boreholes, major units of deformed and/or fractured rock have been distinguished (cf. Figures 3.9-3.13). These major units exhibit anomalous physical properties and therefore cause marked responses on several logs. The major units generally constitute the more low-resistive sections in the boreholes, i.e. about 20-30 kOhmm compared to the background level in the more competent rock which is higher than 100 kOhmm. The most significant units are found in W1 and W2.

In general both sonic and single point resistance anomalies occur at the main units. However, sonic anomalies occur rather frequently elsewhere. Both the sonic and the single point resistance methods have shallow penetration depth and are more or less sensitive to disturbances close to the borehole wall. Some anomalies probably reflect mechanical damage of the borehole wall caused by drilling.

The results from the single hole geophysical logging are shown in Figures 3.9-3.13. The location of the major features are indicated in these figures and it is evident that most anomalies occur within the defined features.

The specific geophysical character of the deformed units enable correlation of some of the units between the boreholes, assuming the units to be planes. The main direction of the units seem to be N-NNW and
steeply dipping. Apart from these zones the granite is relatively competent. Pegmatites and concentrations of darker minerals have been recognized.
Figure 3.9 Composite log of data collected along borehole N2.
Figure 3.10 Composite log of data collected along borehole N3.
Figure 3.11 Composite log of data collected along borehole N4.
Figure 3.12  Composite log of data collected along borehole WI.
**Figure 3.13** Composite log of data collected along borehole W2.
3.3 HYDRAULIC EVIDENCE OF FRACTURE ZONES

3.3.1 Crosshole hydraulic responses

Previous work in the Crosshole Project has shown that when hydraulic disturbances are created in one borehole the response in adjacent boreholes is limited to small zones. This is taken to infer that the response is channelled within a particular region, probably a fracture zone. These so-called "crosshole responses" are seen as the best indicator of the hydraulic importance of a geophysically identified fracture zone. However, although the first stage of the SCV project was designed to include only single borehole testing to gather data on the hydraulic properties of the fracture sets, there were effectively a few "qualitative" crosshole tests.

During the single borehole testing of boreholes N3, N4, and W1 a few "crosshole responses" were noted. These were caused by opening and shutting the complete length of borehole W2. Obviously at the time when borehole W2 was opened the single borehole testing string was positioned at a specific location in one of the other boreholes. Hence, there are a few specific sections surrounded by a "rest of borehole" section.

The responses are summarized in Figure 3.14 which shows that the whole of W1 responded, the closest third of N3 and only 2 short sections in N4. The responses have been converted to a "speed of response" in metres per minute based on the distance to the closest part of borehole W2. No inferences can be drawn on the position of the source of disturbance within W2 even though the spreading sections obviously "tie in" with the geophysically identified features.

It is clear from the responses that the opening and shutting of W2 propagates a signal right across the site. These periods of opening and shutting were however quite short lasting for 55 minutes in the case of W1, 99 minutes for N4, and 89 minutes for N3. It should be borne in mind however that when W2 was opened for 18 days at the end of April 1987 that the pressure drop was observable in every borehole in the SCV area. Lack of knowledge concerning the exact position of the source within W2 and the flow geometry of the fracture zones of the site makes a detailed hydrogeological interpretation of the responses impossible.
3.3.2 Head distribution

The distribution of head within the site is largely controlled by the occurrence of zones of high transmissivity and where they intersect regions of low head (i.e. drifts or mine workings). The head has been measured around the site both during the single borehole testing and using the Piezomac automatic head monitoring system (plus some manual measurements). Tabulated measurements are available from December 1986 to December 1987 (see Carlsten and others, 1988). The single borehole testing occurred during the second half of this period. Apart from the 3 boreholes in the "3D Drift" and some long sections in N1, the heads have been measured in complete undivided boreholes. This has the effect of averaging out all the head variations. These averaged heads were compared with the results from the single borehole testing and it was found that the long term equilibrium monitored heads were averages of the single borehole test results. This was taken to mean that the single borehole results were effectively small section results equivalent to the condition in which the whole borehole is sealed. These results have been plotted relative to the 360 m level (see Figure 3.15) together with some historical data from the BMT area (actually taken from the SAC period).

The plan of the heads (Figure 3.15) only shows heads measured within 25 m of the 360 m level (i.e. 335 m-385 m). Hence the bottom ends (i.e. the northern) of N2, N3 and N4 have not been plotted.

The map of heads shows some consistent results around the 3D Drift where there are steep gradients immediately adjacent to the drift. This indicates an absence of highly transmissive features draining into the 3D Drift. Borehole N2 shows a head drop where it passes underneath the access drift to the 3D experimental area. The most marked hydraulic feature in the area is the low head anomaly in borehole N3 where it is cut by the gently dipping fracture zone named GC. Other aspects of the head distribution are the lack of individual features in the W2 borehole and the higher heads close to the 3D Drift compared to those in the NW of the site. It should be remembered that the mine cavity and its associated access drifts lie to the south east of the site and that therefore the area furthest away should have the highest heads. The relatively constant heads (around 180 m less than hydrostatic) in the NW of the site require explanation. Some form of major "sink" needs to be inferred in that region.
Figure 3.14

Short-term disturbances in borehole WZ.

Responses observed in adjacent boreholes due to...
Figure 3.15 Map of measured heads between 335 m and 385 m below ground in the area of the SCV Site. Datum is 360 m level.
3.4 HYDROCHEMISTRY

3.4.1 Introduction

The aim of the hydrochemical investigations is to distinguish between different groundwaters and hence different groundwater flow paths within the fractures occurring at the site. Only major constituents plus the isotopes of water and total uranium have been measured for this purpose. The sampling was guided strongly by the results of the hydraulic testing and only zones with hydraulic conductivity in excess of $10^{-8}$ m/s have been sampled. The 3 N-boreholes were sampled more comprehensively than the 2 W-boreholes (see Figure 3.16 which shows all zones above a threshold of $10^{-9}$ m/s). Samples were collected after a total flow of 5 system volumes and were filtered through a 0.4 micron filter.

3.4.2 Results

The detailed results of the chemical analyses are given in Wikberg et.al. (1988) and are summarised here. The pH of most groundwater samples range between 8.6 and 9 and carbonate concentrations are typical of "non-saline Stripa waters" (Nordstrom and others, 1985). Two samples from N2 had a lower carbonate concentration coupled with higher pH and above average chloride concentrations. Iron concentrations are low, still the presence of ferrous iron and sulphides indicates reducing water. In some slowly flowing zones there is a chance that sulphide and iron have oxidized during collection. Tritium data indicate that the samples contain some very young water. The large spread of uranium concentrations suggest mixed oxidizing and reducing groundwaters. High concentrations of organic carbon in some of the groundwater samples results from contamination by plastic tubing.

3.4.3 Interpretation in terms of major features

The water can be classified as saline and non-saline on the basis of chloride content (above 120 mg/l and below 60 mg/l). All the saline waters were collected from the conductive sections of N2 and N3 and the non-saline from N4, W1, and W2.

The saline waters can be further divided into two groups based on the pH and carbonate concentration.
The group with the highest pH and the lowest carbonate content also has the highest chloride concentration. This group is called A2 and consists of the water samples collected at 95 m and 137 m length in the borehole N2. Due to the extremely low flow in these sections it is possible that the salinity might have increased with time if the sampling had been continued.

The second group of saline waters, called A1, consists of the water from all the three levels in borehole N3 and the deepest level of N2. By mixing the non saline waters with A2 type waters the result would be water with a composition similar to type A1 waters.

The non saline waters, group B, cannot be divided into subgroups. The minor variations in the composition of these groundwaters could reflect varying chemical conditions in the fracture systems which they have moved through. Only the water from 102 m in N4 is significantly different from the others. The chloride concentration is slightly higher and the carbonate concentration is slightly lower than in the other waters, indicating a mixing with a more saline water. This is in good agreement with the results of the temperature and salinity measurements that were made in the borehole immediately after it was drilled (Fridh, 1987). The salinity increased rapidly at 85 m of borehole length.

The typical values of the concentrations of major components and the variation within the different groups are given in Table 3.2.

<table>
<thead>
<tr>
<th>Group</th>
<th>Cl/mg/l</th>
<th>HCO₃/mg/l</th>
<th>Na/mg/l</th>
<th>Ca/mg/l</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2 (N2:137)</td>
<td>230</td>
<td>15</td>
<td>110</td>
<td>48</td>
<td>9.4</td>
</tr>
<tr>
<td>(N2: 95)</td>
<td>170</td>
<td>27</td>
<td>110</td>
<td>27</td>
<td>9.6</td>
</tr>
<tr>
<td>A1 (N2:152,N3)</td>
<td>130(10)</td>
<td>50(3)</td>
<td>70(5)</td>
<td>30(2)</td>
<td>8.7(1)</td>
</tr>
<tr>
<td>B (N4,W1,W2)</td>
<td>40(10)</td>
<td>90(10)</td>
<td>45(5)</td>
<td>18(3)</td>
<td>8.6(2)</td>
</tr>
</tbody>
</table>

In order to check the quality of the results the calcite saturation index of all the waters were calculated by the PHREEQE computer code. The calculations show that the waters are saturated with
respect to calcite within ±0.3 log units with only a few exceptions. This confirms that the pH measurements and the analyses of the calcium and carbonate concentrations are correct and that the waters have not been recently mixed, e.g. due to sampling activities.

In the Stripa mine there are two factors which are significant for estimates of groundwater residence time. These are the drainage of the mine and the occurrence of saline water at depth in the rock mass. The radioactive isotope tritium (³H) has a half life of 12 years and is thus an excellent tracer for young (or shallow) groundwater. The existence of detectable amounts of tritium in both the saline and the non saline waters suggest that they include portions of both young and old water. The tritium and uranium data together point out the fact that fast channels carrying oxidizing water are connected to the conductive sections of the SCV boreholes. This situation is valid in the W-boreholes and in N4. The waters have reached equilibrium with respect to calcite but the high uranium concentration indicates that the freshwater portion has not fully equilibrated with the reducing old water.

The redox conditions are defined by the concentrations of iron, sulphur, and uranium. The redox buffer capacity of the water samples is extremely small, even though the reducing character of the waters is demonstrated by the presence of ferrous iron and sulphide. However, the presence of high uranium concentrations in some of the samples indicate a mixing between oxidizing and reducing conditions.

Based on the uranium, tritium, and chloride concentrations in the water a flow model for the SCV Site has been constructed (Figure 3.17). Old saline water flows up through the vertical feature GH. The subhorizontal feature GB which cuts GH contains a mixing of the saline and the non-saline water. Even though portions of very old and very young water are detected the main portion of water is still of intermediate type. In each of the sampling points the portions of the young, intermediate, and old water can be considered to represent the flow downwards, horizontally, and upwards respectively.
Figure 3.16 A schematic illustration of the hydraulic conductivity and the borehole sections which have been sampled (shaded).
Figure 3.17 The saline water (A2) is flowing up in the vertical fracture zone GH because of the drainage of the mine. In the subhorizontal fracture zone GB the saline water (A2) is mixed with the non-saline (B) water. The result of mixing is the water of A2-type.
3.5 DISCUSSION OF EVIDENCE

This section summarizes the information given in the previous sections and presents a combined interpretation of the data collected by the different investigation methods. A description is given of the location and characteristics of the major features identified at the SCV-site. This corresponds to the deterministic part of the conceptual model of the SCV-site.

As described above the existence and location of the major features are based essentially on the results from the radar and seismic surveys. However, there are some differences between the radar and seismic results which can lead to ambiguities in the interpretation. The differences are most clearly evident in the tomograms where the same type of representation of results is made. The radar and seismic tomograms are basically similar but there are some differences with respect to details and these differences have to be reconciled in some manner. It should also be recognized that the radar and seismic data contain errors which could lead to differences in the resulting tomograms. Artifacts in tomograms are mainly caused by errors in time and amplitude picking, quantization errors, offset errors in time and gain, coordinate errors, and incomplete ray coverage. Methods for correcting errors, effects of remaining errors and ray coverage on the tomograms are described by Ivansson (1984), Olsson, Eriksson, Falk, and Sandberg (1988).

In the evaluation of this data set we have aimed at a description of the major features where we can be confident about their existence and location. This means that a major feature has only been considered to exist at those locations where radar and seismic anomalies coincide. There are also some locations where there is a relative displacement of radar slowness and attenuation anomalies. These displacements are considered to reflect the distribution of the corresponding electrical properties in the rock (permittivity and conductivity). The hydraulic significance of the relative spatial displacement of these properties is currently not well understood but the current hypothesis is that permeability mainly is linked to the slowness anomalies (Olsson, Eriksson, Falk, and Sandberg, 1988). To arrive at a consistent model little weight has been given to smaller anomalies. The information from the tomograms have also been weighted against the data from the single hole investigations. It should be recognized that even if the single hole data cannot be used to define the
orientation of features it gives the most accurate information on the intersection of these features with the boreholes.

The data collected along the boreholes are presented as composite logs in Figures 3.9-3.13. The location of the features contained in the conceptual model is indicated. These features have been annotated with 'G' as an initial letter to indicate that it is the result of an integrated analysis of all available data. The second letter has remained the same as in the radar and seismic interpretations whenever possible.

The location of the major features in the N2-N3-N4 and W1-W2 planes is indicated in Figures 3.18 and 3.19. In these figures the width of the zones is indicated schematically. A detailed description of each feature and the evidence supporting its existence and orientation is presented in the following subsections. The data pertaining to each feature is summarised in Tables 3.3-3.8 which include data on intersections with the boundary boreholes and single hole observations made at these intersections, data on the average orientation, and an estimate of the linear dimensions of the feature. The centre point represents a known location of each feature located within the SCV-site. The centre points are located either in N3 or W1 depending on the orientation of the feature.
Figure 3.18 Location of major features contained in the conceptual model in the N2-N3-N4 plane.
Figure 3.19
Location of major features contained in the conceptual model in the W1-W2 plane.
3.5.1 Feature GA

The feature named GA is clearly seen in both the radar and seismic tomograms in the N3-N4 section. GA strikes NE and can also be seen in N2-N3 section of the radar tomogram. The exact location of GA in this part is uncertain as it appears in a part of the tomogram where the spatial resolution is relatively poor. The magnitude of the radar slowness and seismic velocity anomalies becomes smaller towards borehole N4 and it is evident that the feature changes character about 15 km east of N4. The single hole anomalies associated with the feature at its intersection with N4 are also relatively minor. A characteristic of this feature is its bulging shape just west of its intersection with N3.

GA is observed as a relatively strong radar reflector from boreholes N2, N3, and W1. Weaker reflections are observed in N4 and W2.

There is significant fracturing and faint red colouring of the core at the intersection of the zone with N3. There are also resistivity, sonic, and neutron anomalies at this intersection. Similar anomalies are observed at the intersection with W2. There are no significant hydraulic anomalies associated with the intersections of this zone with the boreholes. However, a relatively large conductivity anomaly appears at the edge of the intersection with W2 (3x10^{-8} m/s at 138-140 m). The total hydraulic transmissivity of this zone measured at its intersections with the boreholes is approximately 39x10^{-9} m^2/s which is 1.2% of the total transmissivity measured in the boreholes. If we, in order to account for flow along the edges of a zone, also attribute measured transmissivity within 3 m to each side of the zone intersection (as specified in Table 3.3) to the zone, we get a total transmissivity of 100x10^{-9} m^2/s (3.1%) for GA.

The orientation of the zone is well established in the N2-N3-N4 section where it is observed in the tomograms. The dip of the zone has been approximated from radar crosshole reflection data and a suitable candidate feature has been sought for in the W1 and W2 data. GA is considered to intersect at the end of W2 and there are radar reflection data from W1 and N4 to support the interpreted location and orientation of GA.

The actual and inferred intersections of GA with the boreholes are listed in Table 3.3 together with notes on its character at the borehole intersections. An estimate has also been made of the lateral extent of
the feature. It is observed for a length of about 70 m in the N2-N3-N4 section. It intersects the line of N2 at 227 m which implies that if we consider it to begin 15 m east of the line of N4 we have observed it over a length of at least 120 m. An extrapolation of the feature towards northeast would give an intersection with the line of N1 in the interval 310 to 350 m. In the radar data from N1 a radar reflector is observed which intersects the line of N1 at 338 m which has an intersection angle (38°) compatible with the orientation of GA. This would give GA an extent of at least 250 m. As this correlation between the holes is uncertain GA is considered to have a lateral extent of about 100 m possibly extending further towards NE outside of the site.

Table 3.3 Summary of data associated with the feature GA.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Intersection</th>
<th>Single hole observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>227 ±4 m</td>
<td>inferred intersection, strong radar reflector</td>
</tr>
<tr>
<td>N3</td>
<td>163-171</td>
<td>geophysical anomalies, high fracture frequency and faint red colouring, low hydraulic conductivity, radar reflection of medium strength</td>
</tr>
<tr>
<td>N4</td>
<td>153-156</td>
<td>small resistivity and sonic anomaly, fractures with chlorite, low hydraulic conductivity, weak radar reflector</td>
</tr>
<tr>
<td>W1</td>
<td>210 ±10 m</td>
<td>inferred intersection</td>
</tr>
<tr>
<td>W2</td>
<td>140-145</td>
<td>geophysical anomalies, core loss and high fracture frequency, hydraulic conductivity anomaly at 138-140 m (3x10^{-5} m/s)</td>
</tr>
<tr>
<td>V3</td>
<td>93 ±10 m</td>
<td>inferred intersection</td>
</tr>
</tbody>
</table>

Orientation: N040°E/35°S
Centre point: N3/167m
Extent: =100 m

3.5.2 Feature GB

The feature GB is seen most clearly in the radar attenuation tomogram from the N2-N3-N4 section. The seismic indications of this feature are very weak in the N2-N3 section while there is good agreement between radar and seismic results in the N3-N4 section. The geometry of the feature between boreholes N3 and N4 appears to be quite complex. In this region GB intersects the circular feature RQ
which appears in the radar attenuation tomograms. Large low seismic velocity and radar slowness anomalies appear in the centre of the circular feature. Between N4 and RQ there is a lack of agreement between the different radar and seismic tomograms. This might be caused by artifacts generated by RQ. The final interpretation shown in Figure 3.18 is that GB extends to the centre of RQ and has its western boundary at this location. It is likely that GB extends westwards as a significantly weaker feature. In this case its expected intersection with N4 is in the interval 123-129 m.

The location of GB in the N2-N3-N4 plane essentially determines its strike. The dip has been found from radar crosshole reflection data and by matching with suitable features in the W1-W2 section. A relatively weak feature in the W1-W2 tomograms has been associated with GB which gives a dip of approximately 40° south. This interpretation is supported by radar and seismic reflection data from the W1 and W2 boreholes.

GB is associated with relatively minor single hole anomalies in the N-boreholes. The anomalies encountered in the W-boreholes are more significant. Significant hydraulic conductivity anomalies appear at the intersections with N2 and W2. The fraction of the total hydraulic transmissivity attributed to this feature is about 4 %, which corresponds to $127 \times 10^{-9}$ m$^2$/s.

The intersections of GB with the SCV-boreholes are listed in Table 3.4. GB intersects all boreholes at the SCV site except V3. It is expected to intersect the line of V3 22 m below the bottom of the borehole. GB is considered to extend eastwards from a position about 20 m east of the line of N4 and past N2 (Figure 3.18). This implies that we can follow it for a length of about 150 m. The known vertical extent is essentially determined by the distance between the N and W boreholes and can be estimated to at least 50 m.
Table 3.4  
Summary of data associated with the feature GB.

<table>
<thead>
<tr>
<th>Borehole Intersection</th>
<th>Single hole observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2 184-190</td>
<td>small geophysical anomalies, red colouring of core, tectonite at 191 m, large hydraulic conductivity anomaly, radar reflection of medium strength</td>
</tr>
<tr>
<td>N3 130-135</td>
<td>small geophysical anomalies, few fractures, small hydraulic anomaly, radar reflection of medium strength</td>
</tr>
<tr>
<td>N4 123-129</td>
<td>geophysical anomalies, high fracture frequency, small hydraulic anomaly, weak radar reflection</td>
</tr>
<tr>
<td>W1 132-137</td>
<td>geophysical anomalies, mylonite and red granite, pegmatite at 137.5 m, few fractures, no hydraulic conductivity anomaly, radar reflection of medium strength</td>
</tr>
<tr>
<td>W2 87-92</td>
<td>geophysical anomalies, high fracture frequency, large hydraulic conductivity, radar reflection of medium strength</td>
</tr>
<tr>
<td>V3 72 ±5 m</td>
<td>inferred intersection, radar reflection of medium strength</td>
</tr>
</tbody>
</table>

Orientation: N040°E/40°S  
Centre point: N3/132m  
Extent: =50 m to W and =100 m to E

3.5.3  
**Feature GC**

This feature is seen in the N2-N3 seismic velocity and radar attenuation tomograms and strikes in a northeasterly direction. There is a relative displacement between the radar and seismic anomalies where the seismic anomaly is located about 10 m north of the radar anomaly. As the seismic tomography section covers only a part of the extent of the feature it has been considered less reliable and the position of the radar anomaly is considered to represent the location of GC. There is, however, a discrepancy between the radar data and the single hole data. Single hole anomalies appear at approximately 95 m in N2 while radar data (tomography and reflection) indicate an intersection with N2 at 85 m. This discrepancy is currently not resolved.

Radar reflection data indicate a dip of the zone similar to that of GA and GB. A potential candidate feature in the W1-W2 plane intersects W1 at 43 m and
W2 at the beginning of the hole. This feature is uncertain as it appears in a part of the W1-W2 section where the resolution is poor and at the intersection with W1 the feature might get mixed up with anomalies associated with GH. Fractures with small dip and water inflows in the middle of the 3D-migration drift might be associated with this feature (Abelin and Birgersson, 1988). Still the dip of this zone must be considered uncertain as the information on this feature from the W1-W2 plane is not very reliable.

The single hole anomalies associated with GC are generally minor, except for the relatively large hydraulic conductivity anomaly in N2. Based on single hole and crosshole data GC, is considered to be a minor feature. The hydraulic transmissivity of this feature which is \(36 \times 10^{-9} \text{ m}^2/\text{s}\) (or 1.1% of the total transmissivity) is almost entirely due to its intersection with N2.

The distance between the intersections of GC with N2 and N4 is approximately 140 m. This would indicate an extent of GC of this magnitude. Considering the difficulty to identify the zone in the W1-W2 plane and the 3D-migration drift the extent of the zone is not likely to be greater than this.

Table 3.5 Summary of data associated with the feature GC.

<table>
<thead>
<tr>
<th>Borehole Intersection</th>
<th>Single hole observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2 85±2 or 95±2</td>
<td>extent of zone in this part uncertain, geophysical anomalies at 90-95 m, large hydraulic conductivity anomaly at 97 m, radar reflection of medium strength</td>
</tr>
<tr>
<td>N3 45-48</td>
<td>sonic anomaly, few fractures and core loss, weak radar reflection</td>
</tr>
<tr>
<td>N4 23-29</td>
<td>small resistivity anomaly, crushing of core</td>
</tr>
<tr>
<td>W1 43±2 m</td>
<td>extent of zone in this part uncertain, possible anomalies mixed up with GH</td>
</tr>
<tr>
<td>W2 0</td>
<td>inferred intersection</td>
</tr>
<tr>
<td>V3</td>
<td></td>
</tr>
</tbody>
</table>

Orientation: N040'E/35'S  
Centre point: N3/47m  
Extent: <=150 m
3.5.4 Feature GH

Feature GH is clearly seen in all four radar tomograms from the W1-W2 section. It extends in a northerly direction almost perpendicular to the boreholes. This zone is characterized by a spatial displacement of the attenuation and slowness anomalies. In the attenuation tomograms (Figure 3.3) two almost parallel features which merge close to both boreholes are observed while the slowness anomaly is located between these features (Figure 3.5).

One possible interpretation is that a zone with fairly large thickness (≈15 m) is observed and that it has different physical properties at the boundaries compared to the interior. A significant increase in attenuation is observed at the boundaries while the slowness anomaly is located in the interior. It should also be noted that the attenuation in the interior region is comparable to that of the surrounding rock. The relative displacement of the slowness and amplitude anomalies is considered to be a true representation of the variation in physical properties in this part of the rock and not an artifact caused by the tomographic inversion procedure. A relative displacement of anomalies can in fact be observed in the raw data, where the location of rays with large increase in slowness and the ones with large increase in attenuation are different. The same effect is also observed in connection to the circular attenuation anomaly (RQ) located between boreholes N3 and N4 where the maximum slowness anomaly is located in the centre of the "ring".

The reason for the displacement between the slowness and attenuation anomalies is currently not well understood. The slowness anomaly has a direct correspondence to the variations in the dielectric constant, which in the environment represented by the Stripa granite is expected to depend on the water content (porosity). Increases in attenuation can be expected both from increased water content and the presence of conductive minerals. One possible explanation is that the slowness anomaly represents regions of increased fracturing leading to significant increases in porosity. The attenuation anomaly could possibly be caused by alteration and formation of clay minerals at the sides of a fracture zone. If this explanation is correct high permeabilities would be expected in connection to the slowness anomaly (in the centre of the zone). It should be observed that this is a tentative interpretation which has to be checked further.
especially with respect to the electric properties of altered and fractured granitic rock.

Feature GH is associated with a seismic velocity anomaly only in the southern half of the W1-W2 section (close to W1). A seismic indication of the feature at its intersection with W2 is obtained in the seismic reflection (VSP) data.

The radar reflections associated with GH in the single hole measurements are generally strong. As the zone is striking North-South it is essentially parallel to the N-boreholes and is therefore not observed in the N2-N3-N4 tomograms. An indication of GH is obtained in the seismic tomogram but the feature is not mapped in its correct location. (Features parallel to the boreholes will generally not be identified when source and receiver points are confined to the boreholes due to the limited angular coverage of rays.) The zone is clearly seen as a radar reflector nearly parallel to boreholes N2 and N3. The distance from N2 to the zone is approximately 27 to 30 m slightly increasing with borehole depth. The corresponding distance from N3 is 18 to 15 m decreasing with borehole depth.

The intersection of the feature with boreholes W1 and W2 gives GH a strike which is essentially N-S. The dip is more difficult to determine from the reflection data and dips in the range 45 to 80 degrees seem to provide acceptable solutions. The dip is most accurately determined by the reflection measurements in N2 and N3 which give the intersection of the zone with the N2-N3 plane. The dip is estimated to 60°E. This dip would give an intersection with the line of V3 at a depth of 98 m. In this hole a suitable candidate reflection is found at 93 m which intersects the line of the borehole with an angle of 25°. This corresponds to a dip of 65°.

There are significant geophysical, geological, and hydraulic anomalies at the intersections of GH with W1 and W2. The width of the zone where these anomalies occur in these boreholes is slightly more than 20 m with the strongest anomalies towards the outer boundaries and anomalies of smaller magnitude in the middle. This raises the question whether GH should be considered as one zone approximately 20 m wide or as two separate approximately parallel zones. In this interpretation the alternative of two separate zones is preferred and they have been named GHa and GHB, respectively, with GHa located east of GHB. In some data, e.g. the radar reflection data from N2 and N3, it is not possible to distinguish
between GHa and GHb, the features will in such cases be considered as a common entity.

The hydraulic transmissivity of GH is $1035 \times 10^{-9}$ m$^2$/s, where transmissivities of GHa and GHb are $588 \times 10^{-9}$ m$^2$/s and $447 \times 10^{-9}$ m$^2$/s, respectively. If GH is seen as a common entity it is responsible for 32 % of the total transmissivity at the SCV-site.

Extrapolating the extent of GH outside of the SCV-site it is expected to intersect the access drift to the 3D-migration drift and the access drift to the Crosshole site. It is also expected to intersect some drifts at the 410 m level. Preliminary checks in the drifts have indicated that the feature appears at the expected locations. From this data we can conclude that GH extends for a length of at least 200 m in the north-south direction.

GH is associated with the most significant single hole anomalies found at the site and is hence the most significant feature at the SCV-site from a structural point of view.

Table 3.6 Summary of data associated with the feature GHa.

<table>
<thead>
<tr>
<th>Borehole Intersection</th>
<th>Single hole observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1 45-53</td>
<td>parallel, seen in radar reflection</td>
</tr>
<tr>
<td></td>
<td>geophysical anomalies, characteristic gamma anomaly, breccia at 48 m, high fracture frequency and red colouring, hydraulic conductivity anomaly, radar reflection of medium strength</td>
</tr>
<tr>
<td>W2 50-57</td>
<td>geophysical anomalies, characteristic gamma anomaly, mylonite at 54 m, high fracture frequency and red colouring, large hydraulic conductivity anomaly, strong radar reflection</td>
</tr>
<tr>
<td>V3 100±10 m</td>
<td>inferred intersection, radar reflection of medium strength at 93 m</td>
</tr>
</tbody>
</table>

Orientation: N355°E/=60°E
Centre point: W1/51m
Extent: >200 m
Table 3.7 Summary of data associated with the feature GHB.

<table>
<thead>
<tr>
<th>Borehole Intersection</th>
<th>Single hole observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>parallel</td>
</tr>
<tr>
<td>N3</td>
<td>parallel</td>
</tr>
<tr>
<td>N4</td>
<td>geophysical anomalies, characteristic gamma anomaly, mylonite at 63 m, increased fracture frequency and red colouring, hydraulic conductivity anomaly</td>
</tr>
<tr>
<td>W1</td>
<td>58-64</td>
</tr>
<tr>
<td>W2</td>
<td>67-72</td>
</tr>
<tr>
<td>V3</td>
<td>small geophysical anomalies, increased fracture frequency, large hydraulic conductivity anomaly</td>
</tr>
</tbody>
</table>

Orientation: N355°E/=60°E  
Centre point: W1/61m  
Extent: =100m  

3.5.5 Feature GI

In the radar reflection data from N2, N3, and N4 there are several reflectors with an orientation nearly parallel to the boreholes in addition to GH (cf. Figure 3.1). These reflectors could indicate the existence of additional significant features with an orientation similar to GH. One such reflector has been identified and associated with data from the W1-W2 plane. This feature has been termed GI and it was not included in the original interpretations of the radar and seismic data.

GI is observed as a radar reflection from N4 at a distance of 15 to 20 m. The feature is weakly indicated in the radar and seismic tomograms from the W1-W2 section. The seismic reflection data indicate the existence of several features parallel to GH and there is a feature at the estimated location for GI. The existence of this feature which intersects the N3-N4 plane east of N4 could explain the termination or change in character of features GA and GB approximately 15 to 20 m east of N4.

GI is associated with single hole anomalies at its intersections with W1 and W2 but it is not considered as significant as GH. Single hole anomalies near GI indicate that there could also exist nearly parallel features of smaller magnitude close to GI. The hydraulic transmissivity attributed to GI is $542 \times 10^{-9}$
m²/s (17% of the total transmissivity). In this case measured transmissivities within 3 m to each side of the defined intersections with the boreholes, as defined in Table 3.8, have been included in the transmissivity estimate for GI. It should be noted that the magnitude of the hydraulic transmissivity attributed to GI is very sensitive to its assigned width.

The lateral extent of GI can be estimated from the N4 radar reflection data. The feature can be observed in the borehole interval 50 to 200 m and the extent in the north-south direction can hence be estimated to at least 150 m.

Table 3.8 Summary of data associated with the feature GI.

<table>
<thead>
<tr>
<th>Borehole Intersection</th>
<th>Single hole observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td></td>
</tr>
<tr>
<td>N3</td>
<td></td>
</tr>
<tr>
<td>N4</td>
<td></td>
</tr>
<tr>
<td>W1 108-112</td>
<td>parallel, seen in radar reflection geophysical anomalies, high fracture frequency, hydraulic conductivity anomaly, weak radar reflection</td>
</tr>
<tr>
<td>W2 127-130</td>
<td>geophysical anomalies, increased fracture frequency, hydraulic conductivity anomaly, radar reflection of medium strength</td>
</tr>
<tr>
<td>V3</td>
<td></td>
</tr>
</tbody>
</table>

Orientation: N345°E/70°E
Centre point: W1 110 m
Extent: =>150 m

3.5.6 Features RK, SK, RL, and SL

The radar and seismic interpretations identified two features named K and L of nearly similar orientation and location. The radar and seismic data supporting the existence of these features have been reviewed together with the single hole data and the evidence for these features has not been considered consistent enough to include them in the conceptual model. However, there is data indicating the existence of features with an orientation similar to that of RK, SK, RL, and SL (i.e. N55°W/65-70°N) even if this data is not sufficient to uniquely determine their location. This might be due to the limited lateral
extent of these features. Feature RK is further discussed in Chapter 5.

3.6 SUMMARY DESCRIPTION OF MAJOR FEATURES

The conceptual model of the SCV-site includes five fracture zones, four of these zones are considered as major features and one as a minor feature. The major features have been given the notations GA, GB, GH, and GI, the minor one is called GC. The location of the zones at two depth levels of the Stripa Mine are shown in Figures 3.20 and 3.21. The location of the features in the N2-N3-N4 and W1-W2 planes is also shown in Figures 3.18 and 3.19.

The zones can be grouped according to their orientation:

<table>
<thead>
<tr>
<th>Zone</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA, GB, GC</td>
<td>N40°E/ 35-40°S</td>
</tr>
<tr>
<td>GH, GI</td>
<td>N5-15°W/ 60°E</td>
</tr>
</tbody>
</table>

Of the two groups of orientations the features which strike NNW tend to be more extensive and more continuous. There are also weak indications of features of limited extent which strike NW and have a steep dip (≈60°) to the north, e.g. RK. As indications of these NW trending features are weak they have not been included in the conceptual model as deterministic features.

A characteristic feature of the zones is that they are irregular, and in the tomograms they appear as a series of connected patches rather than well defined planar zones. These patches in the tomographic images are probably a representation of pinching and swelling of the fracture zones along both dip and strike. In some cases it is also possible to observe faulting, which disrupts the linear nature of the zones. The data give an impression of a set of zones with considerable variation in properties and thickness along the average extent of the zones.

An attempt has been made to summarize the properties of the zones as they appear in the data from the different investigation methods. A qualitative classification of the strength of the anomalies associated with the zones have been made in three classes: Strong, Medium, and Weak. In the comparison
we have included results from radar, seismics, geophysical logging, core logging, and hydraulic single hole tests. In comparing this data it should be recognized that the geophysical logging, core logging, and hydraulic data only pertain to the intersection of zones with boreholes, while the radar and seismic data essentially refer to properties of the zones in the rock mass between boreholes.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Radar</th>
<th>Seisms</th>
<th>Geoph</th>
<th>Core</th>
<th>Hydraulic transmissivity ($10^{-9}$ m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA:</td>
<td>S</td>
<td>S</td>
<td>M</td>
<td>M</td>
<td>100</td>
</tr>
<tr>
<td>GB:</td>
<td>S</td>
<td>S</td>
<td>M</td>
<td>M</td>
<td>125</td>
</tr>
<tr>
<td>GH:</td>
<td>S</td>
<td>S</td>
<td>M</td>
<td>S</td>
<td>1035</td>
</tr>
<tr>
<td>GI:</td>
<td>M</td>
<td>W</td>
<td>M</td>
<td>M</td>
<td>542</td>
</tr>
<tr>
<td>GC:</td>
<td>M</td>
<td>S</td>
<td>W</td>
<td>W</td>
<td>36</td>
</tr>
</tbody>
</table>

From the table it is evident that the major features are clearly identified in practically all of the data sets. The hydraulic conductivities fall in the range $10^{-9}$ to $10^{-7}$ m/s, where the largest values have been observed for GH. GH and GI are the most transmissive features with a total transmissivity an order of magnitude larger than the other features. The width of the major features is in the range 1-10 m, with a possible exception for GH which if seen as a common entity has a width of about 20 m. The minor feature (GC) is not as clearly defined as the major features and the width of GC is about 2 m. The lateral extent of the deterministic features included in the conceptual model range from about 100 m to 200 m. The upper limit is basically due to the limited size of the investigated volume and it is both possible and likely that some of the major features have a greater extent.
Figure 3.20 Location of major and minor features included in the conceptual model of the SCV-site at the 360 m level of the mine.
Figure 3.21  Location of major and minor features included in the conceptual model of the SCV-site at the 335 m level of the mine.
4 FRACTURE SETS

4.1 INTRODUCTION

Fractures in most rock masses exist on a number of distinct but overlapping scales. For the purposes of the present study we are primarily concerned with the regular joints and the fault/shear/fracture zones. The really small scale members of the fracture family such as fissures and microcracks may be important in that they may contribute significantly to the ability of the rock mass to absorb radionuclides but they are not the main focus of this study.

The contribution of a fracture to the transport or permeability properties of a rock mass is determined in part by its dimensions parallel to its plane (its trace length, assuming a given shape) and by its aperture. Both fracture zones and joints have different but finite trace lengths. If the fracture trace lengths can be observed and mapped, the distribution of trace lengths can be characterized by the moments of an appropriate distribution or statistical model.

Since each fracture has a finite trace length the contribution of each fracture to the permeability of the rock mass in which it is located also depends on whether its trace length is long enough to be continuous from flow boundary to flow boundary across the rock block or rock mass being investigated. If the trace lengths of the individual fractures are shorter than the rock mass dimensions, the contribution of a particular scale of fracturing to the rock mass permeability depends on how well the fractures are interconnected. At Stripa the average trace length of the joints is only about one to two percent of the SCV site dimensions. Also, while the length dimensions of the major fracture zones appear to be similar to the dimensions of the SCV block they are discontinuous on the scale of the rock mass in which the block is located. Hence the interconnectivity of both scales of fracturing and the cross connection between both scales is a critical factor in determining the transport properties of the SCV block. However, the interconnectivity of a fracture system is a complex expression of the fracture geometry, that is the distribution of fracture orientations, trace lengths and spacings.
Map showing location of boreholes, scanlines and the boundaries of the six subregions used for assessing the overall variation in fracture geometry at the SCV site.
In the area of the SCV block as with most underground sites the rock mass available for direct observation is limited to the surface of a limited number of drifts (Figure 4.1) with four different orientations. Because of the similarity in cross-sectional dimensions of the drifts and the average trace lengths of the joints, these drifts permit the collection of data on the trace length, and to some extent spacing, and orientation of the joints intersecting the drifts. On the other hand, boreholes (Figure 4.1) close to and through the SCV block provide additional information on fracture orientations and spacings, but no additional information on the trace lengths of individual fractures. Thus, mapping of fractures intersecting drill cores and borehole and drift walls form complementary data sets that should provide a fairly complete picture of the fracture system in a given rock mass. Hence, as part of the SCV Project a systematic program of mapping fractures, that cut scanlines along drifts (Figure 4.1) as well as the fractures intersecting the reconstructed and oriented drillcores and the borehole walls, was carried out in order to characterize the geometry of the fracture system in the SCV block.

The basic objective of the continuing fracture mapping program is to provide a detailed data base that will permit a statistical characterization of the orientations, trace lengths and spacings of each fracture set making up the fracture system. This characterization is designed to provide the basis for predicting and validating the fracture geometry of the test area, integrating the fracture and hydraulic data as well as provide the data needed to generate the fracture network in the test area for both flow and pathway predictions.

The walls of most of the drifts bounding the SCV site were photographed. The photographs were enlarged and used as a mapping base. All fractures, with trace lengths greater than 0.5 m, intersecting seven individual scanlines (Figure 4.1) were systematically mapped as part of Stage I of the SCV Project. Scanlines 1 and 3 are located along the access drift to the 3-D migration test area, scanline number 2 runs the length of the inclined drift leading from the Extensometer drift, where borehole N4 is located, to the 360 m level and scanlines 4, 5, 6 and 7 are located in the 3-D migration test area. All scanlines are horizontal except scanline 2 which has a plunge of 25°. Basic data were collected on fracture orientation, trace length, termination mode, surface characteristics and fracture filling minerals. In addition, a number of fractures adjacent to but not intersecting the scanlines were mapped.
Cores from each of the five boreholes, N2, N3, N4, W1, and W2 (Figure 4.1), were mapped to show lithology, fracture locations, fracture type, relative orientations, fracture minerals and fracture surface characteristics. These cores were reconstructed and the true fracture orientations were determined using relative fracture orientations in conjunction with televiewer and TV camera data. The collar and bottom hole position, orientation, length, etc. of each borehole are given in Table 2.1.

4.1.1 General fracture characteristics

Prediction of fracture geometry over rock masses the size of the SCV block requires a measure of the spatial variability of the fracture geometry. As a first step in determining if the fracture geometry varies over the SCV block we have computed RQD values and the fracture frequency for each borehole. Both parameters were computed from the drill core data and reflect the degree of fracturing or the intensity of fracturing and the degree to which the core is crushed or broken.

RQD values are used in geological engineering to give an indication of the "ground" conditions (Deere, 1964). The RQD value is computed by summing the individual lengths of whole core that are 100 mm or greater in length, in a given drilled interval, and expressing this length as a fraction or percentage of the drilled interval. Complete core recovery with no broken or crushed zones will give an RQD of 1.0 or 100%, i.e. very good rock conditions. Hence, RQD should be a good indicator of fracture or shear zones that are intersected by the borehole.

Figure 4.2 shows the RQD plots for the N holes and Figure 4.3 shows the RQD plots for the W holes. For these boreholes we have calculated the RQD values using a moving average approach, based on an interval length of 2.0 m and an increment of 0.5 m. A similar moving average approach was used to calculate the fracture frequency or the number of fractures per metre. For Figures 4.2 and 4.3 we have used the sealed and coated fractures in calculating the fracture frequency but we have used the sealed, coated, and induced fractures in the RQD calculations.
Figure 4.2 Frequency of fractures per metre and RQD values for the three N boreholes shown in their correct relative position. These plots are based on the coated, sealed, and induced fractures and have been calculated using a moving average with a base length of 1.0 m and an increment of 0.2 m.
Figure 4.3 Frequency of fractures per metre and RQD values for the two W boreholes shown in their correct relative position. These plots are based on the coated, sealed, and induced fractures and have been calculated using a moving average with a base length of 1.0 m and an increment of 0.2 m.

Figures 4.2 and 4.3 clearly show the sections of the boreholes in which there has been core loss or broken core and the sections with very high fracture frequency. However, when we compare the diagrams for the N and W boreholes, it is clear that the W holes intersected many more fractures, up to a factor of two, per metre drilled than the N holes. Also, it appears that the fracturing increases towards the northwest corner of the block.
4.1.2 Fracture orientation

The lower hemisphere contour plot of the probability density of poles to all of the fracture planes measured along the drifts is given in Figure 4.4. The contour values represent density of poles calculated by weighting the density at each point by the angular distance to each of the poles in the sample from the point in question. A visual examination of this contour diagram of poles to fracture planes show that three sets or clusters are defined by the density contours. These sets, while slightly rotated, appear to correspond to three of the sets from the Buffer Mass Test area as labelled in the earlier report by Rouleau and Gale (1985).

The orientation of the drifts and hence the scanlines introduce an orientation bias to the plot of poles to fracture planes (Terzaghi, 1965). Hence a scanline with a given orientation will be more likely to intersect fractures that are oriented sub-perpendicular than those that are oriented sub-parallel to the scanline. Using the approach outlined by Terzaghi (1965) we have computed the blind zone for each scanline and combined them to form a composite blind zone plot (Figure 4.5). In this study, we arbitrarily assume that any fracture plane that intersects a borehole at an angle of ≤20° will not be adequately sampled by that borehole or scanline. This figure shows that the existing scanlines do not adequately sample sub-horizontal fractures that have an easterly dip.

From the reconstructed and oriented core and the corrected relative dip (alpha) and dip direction (beta) with respect to the reference line the true orientation of the fractures intersecting the drillcore from boreholes N2, N3, N4, W1 and W2 were calculated. All of the fracture orientations are given in terms of the mine north. The contour plot of poles to fracture planes for all boreholes are given in Figure 4.6. Boreholes N2, N3 and N4 plunge 18.6 degrees parallel to mine north (which is N10°W with respect to true North), and W1 and W2 plunge 5 degrees in a direction 90 degrees west of mine north (N100°W in relation to true North).

The N boreholes, because of their steeper plunge and hence greater vertical span, intersect a greater percentage of sub-horizontal fractures than the two W boreholes. However, the sub-horizontal fracture planes are oriented sub-parallel to both the N and W boreholes and hence lie within what is generally described as the "blind zone" on the stereoplot.
Figure 4.4  Plot of poles to fracture planes for all fractures from the scanline mapping program. This contour plot indicates three main clusters of fracture sets, a steeply dipping NNE trending set, a steeply dipping NW trending set, and a subhorizontal set.

When the two isogonic plots for the N and W boreholes are superimposed (Figure 4.7), the blind zone for the N and W drillholes is reduced to include only those fractures whose poles have a southerly trend and a plunge greater than 50 degrees, i.e. a limited part of the sub-horizontal fracture set. Thus, the N boreholes should provide a good sample of any East-West trending sub-vertical fracture set and the W boreholes should provide a good sample of any North-South trending sub-vertical fracture set, if these sets are present in the rock mass.

Comparison of the contour plots for each of the N and W boreholes (Gale and Stråhle, 1988) shows that the W boreholes have intersected a strong North-South trending sub-vertical fracture set. However, the N boreholes do not indicate the presence of strong East-West trending sub-vertical set. Instead, the N boreholes show pole clusters in the NE, NW, SE and SW sections of the pole diagrams.
When we combine the 3,100 poles from the N and W boreholes (Figure 4.6) the East-West pole clusters dominate the contour diagram. However a considerable amount of data is lost in the background due to the dominance of the East-West cluster. Data from the scanlines (Figure 4.4) indicate two sub-vertical fracture sets and a sub-horizontal fracture set. When the borehole and scanline data are combined (Figure 4.8) the relative strength of the sub-horizontal set is greatly diminished, indicating the danger of using contour plots of pole densities to define sets or clusters when one does not have an equal number of fractures from each set.
Figure 4.5  Plot of the blind zones for each scanline orientation, assuming a blind zone of 20 degrees on either side of the scanline.
Contour plots of poles to fracture planes for all boreholes, N2, N3, N4, W1, and W2.
Figure 4.7 Composite plot of blind zones for the two borehole orientations. This plot shows that the sub-horizontal fracture set is not well sampled by the N and W boreholes.
Figure 4.8  Contour plots of poles to fracture planes for the combined data set of five boreholes and the scanline fracture data.
4.1.3 Variability in fracture orientation

The fracture pole plots of the N and W boreholes contain significant orientation bias. In order to examine the variability in fracture orientations over the SCV block, we have combined fractures from each of the two boreholes at their points of intersection. This reduces the orientation bias in the data subsets because, while the N and W boreholes are separated vertically, the two boreholes do provide two sampling directions at six points within the rock mass. By selecting 60 fractures from sections of each borehole, centered on the vertical point at which the boreholes cross-over, we have effectively weighted each sample by the fracture density in each borehole. Given the greater fracture density in the W-holes, this prevented the pattern of fracture clusters (Figure 4.9) from being completely masked by the stronger N-S trending fracture set.

Each intersection data set was analyzed using a cluster analysis program, "CLUSTRAN" (Gillett, 1987) to determine the number of fracture clusters or fracture sets, and their mean orientation, in the immediate area of the intersection points. The mean pole direction for each cluster and each cluster number have been plotted in Figure 4.10. From these different pole plots it can be seen that the fracture orientations do vary over the SCV block.

In order to develop the conceptual model for the fracture geometry within the SCV block, we have divided the block into six sub-regions (Figure 4.1). We have extracted from the total data set the fracture data for the N and W boreholes plus the scanlines that are in each sub-region. Each data subset has been analyzed using "CLUSTRAN" to determine the number of fracture clusters or fracture sets in each sub-region. The mean orientation for each cluster in each sub-region is shown on a stereoplot in Figure 4.11.

When one compares the mean pole plots for both the intersection data and the sub-region data one can see that the clusters fall into two main groups - a group that plots in the southwest and northeast quadrants, having a northwest-southeast strike, and a group that plots on the western and eastern borders of the stereonet and hence has a north to northeast strike. Other smaller clusters are scattered over the stereoplots (Figures 4.10 and 4.11). However, the clusters in Figure 4.11a, for the six sub-regions with their larger number of fractures show much tighter groupings than the clusters determined from the data used in Figure 4.9. The variation over the
SCV block is shown much more clearly by comparing the clusters for each sub-region (Figure 4.11b). The location of the mean pole for each cluster is shown by a solid symbol in both Figures 4.11a and 4.11b. In each figure, two numbers are associated with each cluster location. In Figure 4.11a the sub-region number and cluster number is given plus the global cluster number. In Figure 4.11b, the sub-region cluster number is given with the second, underlined, number giving the number of fractures in each cluster. The reader can judge the relative importance of each cluster, in each sub-region, by comparing the number of fractures in each cluster. The degree of clustering can be determined by comparing the standard deviation for each cluster as given by Gale and Stråhle (1988).

For the purposes of this report we consider clusters 1, 3, 4, 7, 9, 10, 11, 13, 16, 19, 20, 21, 24, 26, 27, 30, and 32 to form one group (Cluster A) or set and clusters 5, 12, 14, 18, 25, 28, 29, and 33 to form a second grouping (Cluster B). The other clusters have been placed into a loose third group (Cluster C). It is obvious that, even though two strong fracture sets are present, this is a somewhat arbitrary grouping. Also, it should be noted that the sub-horizontal set or cluster that is present in the scanline data does not appear as strong separate clusters when all fractures are treated equally.

As part of the ongoing analysis of the fracture data, we will examine the degree of correlation of the fracture surface characteristics with the geometry of each fracture in each cluster in order to assess the geological and structural basis for each cluster. In addition, we will conduct a rigorous analysis of the variation in fracture properties over the SCV site. Given the variation in fracture orientations over the SCV block determined from this preliminary analysis, we will have to define a smaller zone of interest for 3-D stochastic network modelling purposes and characterize the geometry of the fracture system within a smaller zone.
Figure 4.9  Pole plots of 60 fractures from each of the N and W boreholes at each of the points where the W boreholes cross over the N boreholes in the plan view.
Figure 4.10  Plot for the mean pole directions for the clusters in each set of 120 fracture planes from the points where the W boreholes cross over the N boreholes. The symbols indicate the location of each cluster from each set of data.
Figure 4.11  Plot of the mean pole directions for (a) all of the clusters in the SCV block and (b) the clusters in each of the sub-regions. The statistics for each cluster are given in Gale and Stråhle, 1988.
4.1.4 Fracture trace lengths

During the mapping of the scanlines, the length of each fracture trace was measured. Based on its orientation, each fracture was assigned to one of the fracture clusters and hence to one of the groups of clusters - group A, B or C. Then for each group of clusters, the trace lengths were plotted as a frequency histogram (Figure 4.12). In addition to showing the distribution of fracture trace lengths, these histograms also indicate the degree of censoring, i.e. 0 when both ends of the fracture trace are visible on the mapped surface, 1 when only one end is visible and 2 when neither end is visible. In addition to the censoring, the trace length data also contain truncation and/or size biases. This makes it difficult to complete a rigorous statistical analysis of the trace length data. As a preliminary step, we applied a maximum likelihood approach (Rouleau and Gale, 1985) to estimate the parameters of the trace length distributions accounting for censoring and truncation and assuming a lognormal model. The degree of censoring was too severe for this particular analysis to be applied to these data. A more robust approach will be applied to the data to provide estimates of the mean and variance that reflect corrections for truncation and censoring.

No tests have been carried out for the goodness-of-fit of this model to these data. However, based on the shape of the histogram, the lognormal model appears to fit the data reasonably well. Also, the raw results suggest that there is a significant difference in the trace lengths between the three major fracture groups. The preliminary statistics for the trace length data are given in Table 4.1.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Obs.</td>
<td>219</td>
<td>382</td>
<td>181</td>
<td>782</td>
</tr>
<tr>
<td>Min. value, m</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Max. value, m</td>
<td>9.0</td>
<td>8.0</td>
<td>11.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Mean, m</td>
<td>1.57</td>
<td>1.20</td>
<td>1.96</td>
<td>1.46</td>
</tr>
<tr>
<td>Std. Dev., m</td>
<td>1.05</td>
<td>1.01</td>
<td>1.43</td>
<td>1.17</td>
</tr>
</tbody>
</table>

In addition to the trace lengths, the nature of the fracture terminations is expected to influence both the flux and solute transport through the fracture
network. During the scanline mapping the termination mode of each fracture was recorded using a system similar to that used to label the degree of censoring. A termination of 0 was used for fractures with both ends terminating in the drift wall, 1 was used for fractures with one end terminating against another fracture, 2 was used for fractures with both ends terminating against other fractures, 3 was used for fractures that ended in a typical splay or horse-tail. Fractures that had a censoring of 1 with one end terminating in the drift wall or a censoring of 2 were placed in a separate category.

Figure 4.13 shows the distribution of trace lengths by termination mode for groups A, B and C. These diagrams show that about 70 to 60% of the uncensored fractures in cluster groups A and B and about 80% in cluster group C terminate against other fractures. This characteristic of the fracture system will affect calculations of the interconnection of the fracture system and will have to be reflected in the network modelling.
4.1.5 Fracture spacings

The spatial locations of the fractures intersecting the drill core were used to compute the spacing between every pair of consecutive fractures of the same set or cluster. We define the spacing here as the distance between consecutive intersections of two fractures of the same set with a sampling line (i.e. a borehole axis), multiplied by the cosine of the angle made by the sampling line and the pole of the average plane of the fracture set. Frequency histograms (Figure 4.14) of spacings for every fracture set have been constructed for each cluster group in the SCV block. A summary of the statistics is given in Table 4.2.

Based on the shape of the histograms in Figure (4.14) we have assumed that the lognormal model is a reasonable fit to the data in each distribution. The distributions will be tested against other models and goodness-of-fit tests will be performed to determine which models do not fit the data at an acceptable level of significance.
### Table 4.2  Spacing statistics from borehole data.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Obs.</td>
<td>899</td>
<td>1280</td>
<td>234</td>
</tr>
<tr>
<td>Min. value, m</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
</tr>
<tr>
<td>Max. value, m</td>
<td>26.3</td>
<td>10.98</td>
<td>44.79</td>
</tr>
<tr>
<td>Mean, m</td>
<td>1.16</td>
<td>0.26</td>
<td>1.86</td>
</tr>
<tr>
<td>Std. Dev., m</td>
<td>2.51</td>
<td>0.59</td>
<td>3.97</td>
</tr>
</tbody>
</table>

**Figure 4.14**  Histogram of fracture spacings computed from the borehole fracture data for each of the three main cluster groups.
4.1.6 Summary

Based on the orientations determined from the drill core data there are significant variations in fracture orientations over the SCV block. Since the validation drift will be located primarily within sub-regions 1 and 2, the orientation data from these sub-regions should be used in the 3-D stochastic modelling. Figure 4-11b shows that six clusters were defined in both of these sub-regions and that the clusters have similar orientations. However, as pointed out earlier the sub-horizontal set that is present in the scan line data is overpowered by the more abundant sub-vertical fractures from drillcores and hence is not adequately represented by the mean values for the clusters in all sub-regions. Hence, care must be taken to use the appropriate standard deviations in generating the individual clusters or sets. The number, strength, and the orientation of the clusters in each of sub-regions 1 and 2 are consistent with the fracture patterns determined from the scan line mapping. Spacing data can be developed for each cluster within each sub-region. However, since the trace length data were obtained from the scanlines on the boundaries of the SCV site we have no measure of how the trace lengths vary over the SCV block.

Given the observed variations in orientations we will define a smaller area of the SCV block, centered on the validation drift, and develop the orientation and spacing statistics for the subset of fracture data contained within this block for the 3-D stochastic modelling. Also, in calculating the distribution parameters for each cluster and generating the fracture network it must be remembered that we have included all of the fractures intersected by the drill holes in determining both the fracture orientations and the fracture spacings. This has produced a double counting of the major fracture zones if the zones are superimposed on the stochastic network as a limited number of discrete fractures of considerable length, since fracture or geophysical zones are defined as being zones of closely spaced fracturing. This double counting has the effect of increasing the average fracture density in the rock between the fracture zones and reducing the density within the fracture zones. In order to adequately model the fracture network we will have to separate the statistics of the fractures forming the fracture zones from those present in the rest of the rock or use a network generator that is not strictly a Monte Carlo approach.
4.2 HYDRAULIC PROPERTIES OF FRACTURE SETS

4.2.1 Testing procedures

The hydraulic properties which are assigned to the fracture sets are, to some extent, affected by the way the testing was carried out. This results from the practical consideration that, with an average of about 4 fractures per metre, 800 m of borehole and an allocated testing period of 6 months, it was impossible to test each fracture individually. However, it was also clear from previous work at the Crosshole Site that flow is dominated by just a few fractures. A testing procedure (see Holmes, 1989) which focussed time and resources on the most transmissive fractures was devised.

The procedure uses an "active packer string" to vary the length of the straddle interval (see Black, in press). The procedure entails installing a 5 packer string into a borehole. In this programme 5 packers, each a metre long, were each separated by 1 metre straddles hence a 9 metre string. Initially the two outermost packers are inflated. If the average hydraulic conductivity of the 7 m straddle exceeded $1\times10^{-11}$ m/s then the central packer was inflated (to create 2 zones each of 3 m length). The two new zones were then tested to determine their average hydraulic conductivity and if either of them exceeded $1\times10^{-10}$ m/s it was again subdivided by inflating the remaining packer which it contained. The advantage of this procedure is that a short test interval is only used for higher transmissivities. The procedure affects the form of the data derived from the testing. Primarily the choice of minimum packer spacing and the thresholds affect the number of the fractures which are tested individually. It also results in a data set where the tests overlap and in some cases some zones are entirely contained within longer intervals. For fastest testing the thresholds are set high. A balance between minimum spacing and upper threshold needs to be achieved to gain optimum results within a reasonable period.

Other innovations were included in the equipment (see Figure 4.15) constructed specifically for the task. These included computer controlled testing procedures, real time analysis of the results and packers with minimal compliance (see Holmes, 1989).

The programme of testing was designed to include pulse and slug testing with some constant flow testing of the most transmissive zones. There was also a programme of constant head testing aimed at
Figure 4.15
General diagram of hydraulic testing equipment.

defining the boundaries of the fractures and their distance from the tested borehole.
4.2.2 Results of hydraulic testing

Each of the five boreholes N2, N3, N4, W1, and W2 were tested using the five packer string and the "threshold" procedure known as Focussed Packer Testing. This produced a set of raw results, including sections of 7, 3, and 1 m length which overlapped. This raw data set required processing in order to "deconvolute" a continuous profile of hydraulic conductivity (K) from the overlapping results. The procedure is detailed in Black and others, 1987, pp 41 and 42. It is based on deconvoluting from lowest values upwards. This is because most practical errors (i.e. such as packer by-pass, valve leakage etc.) tend to raise the derived value of K. Hence, a long section wholly containing a central shorter section of lower K would deconvolute into 3 sections, the central section with the K as measured with two adjacent sections with a K value greater than the original long section. They would be greater by an amount proportional to the difference between the two measured values and the lengths of the sections. The deconvoluted profile should still be compatible with the measured values of transmissivity but each straddle will contain a depth-varying value.

Deconvolution is not always simple as summed transmissivities for 1 and 3 metre sections may not equal that of the 7 metre section due to leakage around the packers or other problems. Also, if a packer covers a transmissive section the calculation of transmissivity for that part of the borehole may be in error to some small degree. The "deconvoluted" data shows more detailed variation where transmissivity values are highest (see Figure 4.16). The data has been plotted according to position within the SCV site in order to show the spatial distribution of transmissivity. N3 was the first borehole tested using the new equipment and the most detailed testing procedures were omitted from this borehole. However, it can be seen that the boreholes vary significantly both in terms of total transmissivity as well as the manner in which it is distributed (see Table 4.3).
Table 4.3 Summary of transmissivity data for boreholes N2, N3, N4, Wl, and W2.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Tested interval (m to m)</th>
<th>Total borehole transmissivity $(m^2/s)$</th>
<th>Frequency of mapped &quot;open&quot; fractures in tested sections (per metre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>7.9-194.9</td>
<td>$2.9 \times 10^{-7}$</td>
<td>1.2</td>
</tr>
<tr>
<td>N3</td>
<td>8.9-182.9</td>
<td>$6.5 \times 10^{-7}$</td>
<td>2.4</td>
</tr>
<tr>
<td>N4</td>
<td>8.0-174.9</td>
<td>$7.5 \times 10^{-7}$</td>
<td>3.7</td>
</tr>
<tr>
<td>W1</td>
<td>8.0-135.1</td>
<td>$2.9 \times 10^{-7}$</td>
<td>4.5</td>
</tr>
<tr>
<td>W2</td>
<td>7.9-140.7</td>
<td>$33.4 \times 10^{-7}$</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Although borehole W2 is the most transmissive it and W1 contain sections of high transmissivity regularly throughout their length. The north running boreholes appear to contain distinct zones of increased transmissivity, though borehole N2 contains more than the other two. There seems to be no direct relationship with fracture frequency.

However, the intention of the testing and core mapping was to examine the relationship between open fracture orientation and transmissivity distribution. Information on the fractures, including location in the borehole, orientation, and direction of dip and fracture type is based on the core logging reported above.

The first step in the analysis of the results in terms of fractures rather than zones is to allocate a transmissivity to each "coated fracture". Only those fractures designated as "coated", and therefore likely to contain water, have been used. First of all the contribution of the matrix conductivity is removed.

The matrix conductivity was assumed to be equivalent to $10^{-12}$ m/s and hence was invariably negligible compared to the value of transmissivity in the fractures.

Once the fracture transmissivity is derived it should then be possible to allocate transmissivity to each fracture. Unfortunately the minimum packer spacing used was 1 m which compares unfavorably with the average number of mapped "coated" fractures per metre (between 1.2 and 4.5). The original intention of the "focussed" testing scheme was to measure individually as many as possible of the most conductive fractures. Hence, examining the tests to see how many "coated" fractures were contained in each tested interval.
yields the distributions shown in Figure 4.17. It can be seen that less than 10% of the tested sections contained single fractures and that many of these were within the lower value ranges. In fact it can also be seen that about 6% of all tests contained no mapped "coated" fractures at all. There would be no problem with this percentage if the derived values reflected non-fractured rock. However, the measured values are distributed across the range of values (see particularly borehole N2). This is probably due to several possible causes; either the location of the packers is not exactly coordinated with the core logging, the test equipment was leaking, some conductive fractures were not identified in the core logging, or that some of the matrix rock is highly conductive. The location problem is considerable when fracture spacings on the order of 1 fracture every 200 mm are considered, also bearing in mind that the core logging datum is not necessarily available for the test. Leaking equipment is likely to occur throughout the testing and was checked for. The borehole with the large amount of no-fracture transmissivity did have some problems with leaking valves. The identification of "flowing" fractures on the basis of being "coated" is problematical. If anything, it is likely that too many rather than too few fractures have been identified. It is unlikely that there are significant amounts of conductive matrix rock at the Stripa site.

Notwithstanding these problems with the data set it was still possible to apportion transmissivity to each individual fracture. This can be performed using different strategies such as "equal assignment" or "log normal assignment".

4.2.3 Interpretation of fracture orientations

The transmissivities of individual fractures were deduced by "equal assignment" of the transmissivities within each measured section. This procedure tends to smear transmissivity too equally over all the fractures. However, if there is an orientation of fracture which is much more conductive than other orientations then it should show up. For the purpose of comparing individual fractures, transmissivities are expressed as apertures in μm of plain parallel sided fractures (see Table 4.4).
Table 4.4 Distribution of fracture aperture according to orientation.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Mean aperture (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-40°</td>
</tr>
<tr>
<td>W1</td>
<td>0.69</td>
</tr>
<tr>
<td>W2</td>
<td>0.79</td>
</tr>
<tr>
<td>N2</td>
<td>0.60</td>
</tr>
<tr>
<td>N3</td>
<td>0.48</td>
</tr>
<tr>
<td>N4</td>
<td>0.44</td>
</tr>
</tbody>
</table>

It can be seen from Table 4.4 that there is little difference between fracture sets except for possibly two orientations in W2 and N2. One is a raised set in W2 the other a reduced set in N2.

In borehole W1 the majority of fractures have a dip direction between 40 and 120 and 240 and 320 degrees. However, the mean aperture of all fracture directions is similar. This may result from the generally high fracture frequency. There seems to be no trend with depth either. There are two exceptions, 8-50 m in the 40 to 120 group and 100-135 m in the 240 to 320 group, which have smaller mean apertures.

In borehole W2 the mean aperture is larger than in W1. Unlike W1 where all orientations have similar apertures, fractures dipping between 120 and 240 degrees have a larger aperture than the others. The depth variation shows that fractures from 8 m to 50 m in the hole in the two dominant groups have a lower mean.

In the N boreholes the dip directions are more evenly spread. In N2 the means of the groups are of a similar magnitude compared to W1 except the group of dip directions 280-360° which has a lower mean than the others. In N4 all the groups have similar means. At depths below 140 m all fracture apertures are smaller.

In summary there may be some indication that there is a set of fractures in W2 (i.e. dip directions between 120°-240°) which is more than averagely conductive. Also there may be an opposite set of less conductive fractures (i.e. dip directions between 260°-360°) in N2. However, the interpretation is not conclusive. Further improvement in correlations might be yielded using sets of fracture orientations which are based
more closely on analysis of the fracture set orientations.

It is generally assumed that the transmissivity of an individual fracture is proportional to the cube of its aperture. If aperture itself is normally distributed then the resultant transmissivities should be "log-normally" distributed. Hence, one could distribute the transmissivity within a given test zone on a non-even basis. However, it would require arbitrarily choosing certain orientations in each section. This can be performed in a number of ways. However, the details of carrying out this procedure together with its implication is beyond the scope of this interim report.
Figure 4.16a The distribution of transmissivity in the boreholes W1 and W2 according to location at the SCV site.
Figure 4.16b  The distribution of transmissivity in the boreholes N2, N3, and N4 according to location at the SCV site.
Figure 4.17a  The dependance on transmissivity of the number of "coated fractures per test section in boreholes W1 and W2.
Figure 4.17b  The dependance on transmissivity of the number of "coated fractures per test section in boreholes N2, N3, and N4.
4.3 MECHANICAL PROPERTIES OF FRACTURE SETS

The surface character of a joint, particularly its roughness and wall strength, determines both the stress-closure behaviour and the shear-dilatation behaviour. Since these two deformation modes have strong influence on the fluid conducting properties, surface characterization is seen to have a fundamental role in the understanding of joint water flow characteristics.

The surface roughness of a joint determines the size and distribution of contact areas and some of the frictional drag effects. The size and distribution of contact areas is also dictated by the ratio of wall strength to normal stress. As this ratio reduces with increasing stress, contact areas are enlarged. Since contacting areas are essentially dead spaces in the joint plane, increased channeling and flow path tortuosity can be expected as wall roughness increases, as normal stress increases and as wall strength reduces.

Fracture surface features such as roughness and compression strength have been measured on individual joints, and the data have been grouped in the two major joint clusters as described in Section 4.1. Measurements of these properties were made on small diameter core samples from boreholes N3, W1, and W2. A total of 201 joint tests have been carried out, 52 of these belong to cluster A, 122 to cluster B, and 27 tests have been performed on non-oriented joints.

The non-linear shear strength formulae for natural rock joints were first described by Barton and Choubey (1977). According to Barton and Choubey (1977) the shear strength, \( \tau \), of rock joints can be described as:

\[
\tau = \sigma_n \tan \left( \text{JRC} \log_{10} \frac{\text{JCS}/\sigma_n}{\phi_r} \right)
\]

where \( \sigma_n \) is effective normal stress.

The joint wall compressive strength (JCS) is measured with a Schmidt hammer. The basic friction angle (\( \phi_b \)) is the friction between two parallel and plane surfaces of the same material as the joint in question. The residual friction angle (\( \phi_r \)) is calculated from the angle \( \phi_b \) and the ratio of Schmidt hammer rebound readings on wet joint surfaces and dry diamond sawn or drilled surfaces.

The joint roughness coefficient (JRC) can be calculated from a simple shear test. The matching joint halves are placed on a tilting table with the
joint surface in a horizontal position, and the angle of sliding is measured.

The results from the core sample measurements are summarised in Table 4.5 where mean values from each cluster are given. The distribution of data values for joint set no. 2 are shown in Figures 4.18-4.20.

Table 4.5 Results from measurements of fracture surface parameters on core samples from boreholes N3, W1, and W2.

<table>
<thead>
<tr>
<th>Set no.</th>
<th>JCS₀</th>
<th>Φᵣ</th>
<th>JRC₀</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120</td>
<td>24.3</td>
<td>7.1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>140</td>
<td>25.5</td>
<td>6.9</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>124</td>
<td>24.9</td>
<td>7.2</td>
<td>27 observations from non-oriented joints</td>
</tr>
</tbody>
</table>

Figure 4.18 Histogram of joint compressive strength for joint set no. 2, strike N-S. 122 observations, median value 140 MPa.
Figure 4.19  Histogram of residual friction angle $\phi_r$ for joint set no. 2. Median value 25.5°.

Figure 4.20  Histogram for joint roughness coefficient for joint set no. 2. Median value 6.9.
Numerical model runs have been performed for joint sets no. 1 and 2. For both sets an initial mechanical aperture $E_0$ at zero normal stress of 100 $\mu$m was used as an input parameter. Figure 4.21 shows the joint behaviour during four loading cycles and corresponding changes in joint conductivity for set no. 2. This cyclic loading is necessary to simulate an undisturbed natural rock joint. The plot of shear stress, dilatation, and conductivity change against shear deformation are shown in Figure 4.22.
Figure 4.21  Cyclic joint behaviour for normal loading of joint set no. 2 with corresponding conductivity change.
Figure 4.22  Shear stress, dilatation, and conductivity change against shear deformation for normal stress of 5, 15, and 25 MPa. Joint set no. 2.
5 DISCUSSION

5.1 DIVISION INTO MAJOR FEATURES AND ROCK MASS

The description of the SCV site has been made in terms of main features and regular joints. The major features are described on an individual basis in terms of location, orientation, extent and physical properties. The geometrical properties of joints such as orientation, trace length, and spacing are described stochastically.

Five major deterministic features have been identified, one of them considered to be of comparatively smaller magnitude. Three of them strike in a northeasterly direction and dip about 35° to southeast. Two of them strike north-northwest and dip steeply (about 60°) to the east. From the stochastic analysis of the joint data it was possible to identify two main fracture orientation clusters. The orientation of cluster A agrees roughly with that of features RK and RI. The orientation of cluster B is very similar to that of GH and GI. Features GA, GB, and GC have an orientation similar to the subhorizontal set that is present in the scanline data. Hence, there is a general agreement between the orientation of the main features and the orientation of individual fractures.

An important aspect of the bimodal division of the rock mass into major features and background rock is whether this representation is appropriate for describing the groundwater flow through the SCV-site in particular and fractured rock in general. A division of this type always involves the introduction of some form of cutoff which determines what is a major feature and what is background rock. The level of cutoff is to some extent arbitrary and there are several reasons for putting it at a certain level. In this conceptual model the basic criteria has been extensiveness, i.e. that a feature can be traced over a length comparable to the distance between the boreholes (about 50 m). An additional criteria has been that the identified features should have anomalous properties compared to those of the background rock. The discussion below focuses on the correlation between hydraulic and geophysical anomalies and the extent to which significant hydraulic transmissivity anomalies do not coincide with the identified features.
5.2 CORRELATION OF HYDRAULIC AND GEOPHYSICAL PROPERTIES

An analysis has been made of the correlation between zones of enhanced hydraulic conductivity, as determined from single hole tests, and various geophysical logs such as single hole normal resistivity, sonic, radar, and fracture frequency. Two methods have been employed. Firstly, a "hit" statistic which allows comparison between the location of specific features and secondly a direct value comparison.

Zones of high hydraulic conductivity were determined from the cumulative frequency distributions of the single hole test results based on the occurrence, per metre, of values of the logarithm of hydraulic conductivity. Results from W1 and W2 were combined to produce a single distribution. The N borehole results were also combined. Both distributions, which are assumed to be log normal, are shown in Figure 5.1 together with means and higher standard deviations. Zones of high conductivity have been selected where the single hole testing results show values greater than the higher standard deviation. Figure 5.2 is a summary diagram showing, by cross hatching in the column, the position of such zones in the five boreholes together with significant geophysical features derived from normal resistivity and sonic logs (zones of maximum disturbance), single hole radar and crosshole radar results.

The "hit" statistics are identical to that presented in Olsson, Black, Cosma, and Pihl, 1987, for the comparison of radar and hydraulic features during the Crosshole investigations. The position of each feature is related to the nearest hydraulic zone. If the feature falls within a zone, it scores zero. If it falls outside, it is given a score equal to the distance of the feature from the nearest zone boundary. When all features have been examined, the scores are summed and divided by the number of features to calculate an average missing score. The average missing distances for an identical number of randomly generated features were calculated based on a computer simulation of one thousand separate sets of features. Comparing the actual missing distance to the distribution of randomly generated missing distances indicates the degree of correlation between features and hydraulic zones. The index used is the percentage of the randomly generated missing distances which are smaller than the actual missing distance. Hence, the lower the index value the better the spatial correlation. Table 5.1 presents the index values for the five boreholes.
Table 5.1 "Hit" statistics for geophysical features.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Normal resistivity</th>
<th>Sonic</th>
<th>Single hole radar</th>
<th>Crosshole radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>11.8</td>
<td>2.3</td>
<td>11.6</td>
<td>5.6</td>
</tr>
<tr>
<td>W2</td>
<td>0.1</td>
<td>0.6</td>
<td>13.8</td>
<td>2.0</td>
</tr>
<tr>
<td>N2</td>
<td>11.4</td>
<td>7.1</td>
<td>11.9</td>
<td>10.5</td>
</tr>
<tr>
<td>N3</td>
<td>0.2</td>
<td>0.01</td>
<td>17.1</td>
<td>36.3</td>
</tr>
<tr>
<td>N4</td>
<td>1.5</td>
<td>0.3</td>
<td>13.5</td>
<td>55.0</td>
</tr>
</tbody>
</table>

The results of this analysis show that both the normal resistivity and sonic log features have good positional agreement with hydraulic zones. There are some features, for example in W1 at 19 m and N2 at 12 and 110 m which are not associated with hydraulic zones. Also some hydraulic zones, e.g. N2 40 m, have no associated sonic or resistivity features. However, the most transmissive zones are associated with features. Single hole radar features are reasonably correlated with hydraulic zones. Crosshole features are well correlated in holes W1, W2, and N2 but badly correlated in N3 and N4. In N4 there is a very significant hydraulic zone at 85 m which has no associated crosshole feature. However, this hydraulic zone coincides with a single borehole radar feature. It is possible that this feature, of limited lateral extent, interconnects with one of the crosshole features.

The second method uses a direct comparison between values of either sonic or resistivity logs, coated fracture frequency and values of hydraulic conductivity. Radar results have not been included as they have no magnitude. In the analysis values from geophysical logs have been averaged over each hydraulic test zone. An example is shown in Figure 5.3 for the sonic log in borehole N4. Results from all the boreholes are given in Table 5.2. In general there is a poor correlation which is inadequate for predictive purposes. Sonic velocity and resistivity are inversely proportional to hydraulic conductivity, i.e. the larger the value the lower the hydraulic conductivity. Fracture frequency is directly proportional to hydraulic conductivity. Table 5.2 also includes results of comparing fracture frequency against sonic and resistivity values in two boreholes. There is again a poor correlation. A more complicated procedure using component analysis could be applied to the geophysical information to obtain a
predictive tool but this is outside the scope of this report.

Table 5.2 Values of correlation coefficient for comparison of hydraulic conductivity with single borehole geophysical logs and fracture frequency.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Normal res</th>
<th>Sonic</th>
<th>Fracture freq</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>0.18</td>
<td>0.36</td>
<td>0.30</td>
</tr>
<tr>
<td>W2</td>
<td>0.50</td>
<td>0.51</td>
<td>0.36</td>
</tr>
<tr>
<td>N2</td>
<td>0.16</td>
<td>0.14</td>
<td>0.28</td>
</tr>
<tr>
<td>N3</td>
<td>0.55</td>
<td>0.48</td>
<td>0.31</td>
</tr>
<tr>
<td>N4</td>
<td>0.54</td>
<td>0.49</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Fracture frequency against single borehole geophysical logs

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Normal res</th>
<th>Sonic</th>
<th>Fracture freq</th>
</tr>
</thead>
<tbody>
<tr>
<td>W2</td>
<td>0.47</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>N4</td>
<td>0.30</td>
<td>0.47</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.1 Distribution of hydraulic conductivity in N and W boreholes.
Figure 5.2 Summary diagram showing location of geophysical features and hydraulically conductive zones in the boreholes.
Figure 5.3

Sonic and hydrostatic conductivity logs from borehole M1 and crossplot of data.
5.3 UNACCOUNTED-FOR SINGLE BOREHOLE ANOMALIES

The identifications of major features as described in Chapter 3 is essentially based on the radar and seismic methods. The basic criterion for identification of these features is the geometrical extent of anomalies observed in radar and seismic data.

The underlying assumption about the major features is that a significant portion of the groundwater flow takes place in them. The hydraulic properties and other characteristics of the identified features are presented and discussed in Section 3.5. It is concluded that major features are associated with increased fracture frequency, signs of tectonization and significant hydraulic and geophysical anomalies as obtained from single hole methods. A measure of the significance of the major feature model of the site is to what extent the major single-hole hydraulic anomalies are accounted for. The significant single-hole anomalies not associated with major features are discussed below.

The question of association of major geophysical features with major single-hole hydraulic anomalies has many aspects concerning definitions. Firstly the major features are defined on the basis of extent and therefore have differing widths where they cut across boreholes. Generally they are assumed to be between three and eight metres thick, averaging five metres. This observations is biased by the direction of the boreholes with respect to the major features. However it cannot be assumed that they are hydraulically continuous (i.e. their hydraulic properties are patchy) and there may be some transmissivity in their vicinity. The question of how to treat the occurrence of major hydraulic anomalies in the vicinity of major features is the essence of how well major features account for major single-hole hydraulics anomalies.

Major single-hole hydraulic anomalies are defined as one metre sections with a transmissivity in excess of $1 \times 10^{-8}$ m²/s. There are 32 such one metre sections which together account for 94% of the total measured borehole transmissivity (amounting to $3.2 \times 10^{-6}$ m²/s).

When significant features are compared with these major hydraulic anomalies there are several major features not accounted for. These are:

- N4 84-91 m Transmissivity = $4.2 \times 10^{-7}$ m²/s
- N2 152-153 m Transmissivity = $8.0 \times 10^{-8}$ m²/s
- W2 78-82 m Transmissivity = $6.5 \times 10^{-7}$ m²/s
The 3 intervals comprise 13%, 2.5% and 20% of the total measured borehole transmissivity respectively. There are a few more transmissive zones each with transmissivities less than 1% of the total which lie outside the major features. However 57% of the transmissivity identified by the single borehole testing coincides directly with the geophysically identified features.

The next question concerns the proximity of the major unaccounted-for hydraulic anomalies to the nearest geophysical feature.

Within the 868 m of the hydrogeologically tested rock there are 18 intersections of major geophysical features. When the finite thickness of zones is taken into the account, this results is an average distance between intersections of 43 m. In other words no test should be more than 21.5 m from an identified zone. In general the region tested by the single hole hydraulic tests can be assumed to be in the order of a few metres. In a few cases where flow is restricted to a single channel this may be seen to extend a few tens of metres. In any case the derived value of transmissivity is dominated by the transmissivity in the immediate vicinity of the borehole (i.e. within a few centimeters of the borehole wall).

Considering the three major unaccounted-for anomalies in turn.

N4: 84-91 m  Transmissivity = 4.2x10^{-7} m^2/s

The hydraulic conductivity reaches a peak value of 2x10^{-7} m/s. In this borehole interval there are also significant resistivity and sonic anomalies. The temperature log shows water flow into the borehole which indicates hydraulic connection to a significant flow system. The crosshole hydraulic data show a rapid head response between this zone and borehole W2 (cf. Section 3.3). At this location there are also significant radar and seismic velocity anomalies in the tomographic data but the tomograms do not indicate that a corresponding feature should extend into the N3-N4 plane. One possibility is that these anomalies are caused by a zone nearly parallel to borehole N4, which could be G1, and that the borehole penetrates a portion of rock just at the end of the zone. This interpretation is supported by radar reflection data and frequent fractures nearly parallel to the borehole axis in this interval.
N2: 151-153 m Transmissivity = 8x10^{-8} m^2/s

The temperature and gamma logs indicate water inflow to the hole and there are also distinct resistivity and sonic anomalies as well as increased fracturing and red colouring of the core. At this location there is also a small aplite dike. These anomalies are most likely caused by the feature RK identified in the radar data (Olsson, Eriksson, Falk and Sandberg, 1988). This feature was interpreted to have an orientation of N305°E/65°N.

There is no strong evidence of this feature in any of the other boreholes and hence it has not been included as a major feature in the conceptual model.

W2: 78-82 m Transmissivity = 6.5x10^{-7} m^2 sec^{-1}

Borehole W2 contains one transmissive interval which has not been related to any major feature. The interval between 78 and 82 m contains the most conductive one metre section measured at the SCV site. The bulk of the flow appears to be due to a few (less than 5) fractures and the corresponding anomalies on the geophysical logs are relatively small, except for the gamma anomaly which indicates a large inflow of water to the hole (Fridh, 1988). This transmissive section is located between features GHb (located 6 m away) and GB (located 5 m away) and it could be that the fractures found in this interval are hydraulically connected to the intersection of these zones.

In summary 57% of the transmissivity is accounted for directly within 10% of the tested rock assigned to the significant geophysical features. Three other hydraulic anomalies account for a further 35% of the total measured transmissivity. It seems likely that the zone in N2 (accounting for 2.5% of total transmissivity) is an isolated value associated with an aplite dike. The other two major anomalies in N4 (accounting for 13%) and W2 (accounting for 20%) would seem to be associated with the edges of major geophysical features and are therefore included within the "accounted-for"-rather than the "unaccounted-for" zones. Thus the geophysically identifies features account for 90% of the measured single borehole transmissivity.

The exercise shows however the difficulties in reconciling data of different type, radii's of influence, resolution and scale. Nevertheless, it should be borne in mind that the geophysical identification is based on the extensiveness of anomalous geophysical parameters. In contrast the single borehole hydraulic results are the product of
rock conditions within a metre of the borehole. A "direct fit" between the two types of data should not be expected.
6 PREDICTIONS

6.1 INTRODUCTION

A central theme in the SCV project is the use of basic measurements at each stage to make predictions about the conditions to be encountered or the nature of specific parameters that will be measured during future stages of the project. The conceptual model as described above essentially contains two parts; the description of location and properties of major features and the statistics on orientations and spacings of individual fractures. The conceptual model can then be used to predict the results of the same type of measurements performed in the new boreholes to be drilled or drifts to be excavated. The resulting agreement or disagreement between the conceptual model and the data to be collected during Stage III of the SCV-project will thus provide a check on the conceptual model. The objective of the Stage III drillings and investigations are twofold; first to provide a check on the conceptual model based on the Stage I data and secondly to provide data for construction of a more detailed and accurate model in the smaller volume around the Validation drift.

Below follows a description of the layout of boreholes and the access drift planned for Stage III of the SCV-project and the rationale for the selected layout. Then follows a description of expected results in the new boreholes.

6.2 LAYOUT OF STAGE III BOREHOLES AND ACCESS DRIFT

The conceptual model as presented above (or actually a preliminary version presented in the Stripa Project Quarterly Report for January-March, 1988) has been the basis for locating the access drift and the C and D boreholes.

The main objective of the C-holes is to characterize a smaller volume around the validation drift in more detail. Two of the most significant zones at the SCV-site are GB and GH. These zones are likely to control the hydraulics in the central portions of the site and they have to be checked with respect to location and properties. The circular feature RQ is also an
anomaly of interest and an attempt has been made to locate the boreholes so that this feature is included in the Stage III investigations. The location of the validation drift has been changed compared to original plans in order to intersect both GB and GH and to make the intersection as perpendicular as possible.

The boreholes have been located in such a way that they originate from essentially the same point (close to the beginning of Wl). In this way each pair of boreholes will define a plane and tomographic surveys between the holes will be possible. The two major zones will be intersected by a large number of boreholes which will facilitate detailed crosshole hydraulic testing of the zones.

Two of the boreholes were given a steep dip in order to provide better sampling in the vertical direction compared to what has been obtained from the boreholes drilled so far.

**Borehole C1**

Location: 360 m level, west wall of drift 1.5 m South of Wl.

- direction 270°
- plunge 38°
- length 150 m

This borehole is intended to intersect GB and GH and provide a check on their orientation. The dip of GH is uncertain and this hole should provide more accurate data.

**Borehole C2**

Location: 360 m level, west wall of drift 2.5 m North of Wl.

- direction 305°
- plunge 40°
- length 150 m

This borehole will provide an additional test on the location and properties of GB and GH.
Borehole C3

Location: 360 m level, west wall of drift 5 m South of W1.

direction 287°
plunge 14°
length 100 m

This borehole is intended as a pilot hole for the validation drift. The hole will be located approximately 25 m above the validation drift at the start of the borehole and will end about 10 m above the end of the planned validation drift. The hole will have the same direction as the validation drift.

Validation drift

The validation drift will intersect zones GB and GH at a relatively steep angle. The validation drift has been oriented in order to minimize the risk of it being nearly parallel to a major zone. The validation drift will be located at the 385 m level of the mine which is approximately in the middle of the investigated volume.

D-boreholes

The D-boreholes will outline the validation drift. There will be 6 boreholes, one in the centre surrounded by five symmetrically placed boreholes. The radius of the perimeter where the boreholes will be located will be 1.2 m. The intention is that the validation drift should have a diameter of 3 m which would make it possible to contain the boreholes within the diameter of the drift.

direction 287°
plunge 3° (down)
length 100 m

The location of the new boreholes, access and validation drift in relation to the mine workings and the existing boreholes are shown in Figure 6.1. Figure 6.2 shows the zones with existing and new boreholes in a vertical section at the X-coordinate 440, i.e. the vertical plane of borehole W1. A perspective view of the access drift and new boreholes in relation to the major features is given in Figures 6.3-6.5. These figures give an indication of the location of intersections between features and between features and drifts and boreholes.
Figure 6.1  Location of C-boreholes, access drift, and validation drift. Solid; 360 m level, dashed; 410 m level.
Figure 6.2  Vertical section at the coordinate X=440 m in the mine system. Location of C-holes, validation and access drift are indicated in relation to the major features GB and GH.
Figure 6.3  Perspective view of main features in relation to C boreholes and the access and validation drifts. Composite of all features (above) and feature GH (below).
Figure 6.4  Perspective view of main features in relation to C boreholes and the access and validation drifts. Feature GA (above) and feature GB (below).
Figure 6.5  Perspective view of main features in relation to C boreholes and the access and validation drifts. Feature GC (above) and feature GI (below).
6.3 INTERCEPTS OF MAJOR FEATURES BY NEW BOREHOLES AND DRIFTS

6.3.1 Introduction

The location and orientation of the major features are given in Section 3.5. The features are as a first approximation considered to be planar. If the extent of the features is extrapolated, intersections with new boreholes and drifts can be calculated. In addition to this, predictions have been made of expected results from measurements in the new boreholes (i.e. the rock properties).

6.3.2 Access drift

The access drift starts at the 410 m level and extends in a northeasterly direction with an ascent of 1:7.5. The access drift is expected to be intersected by GHa at a Y-coordinate of about 1130 m. The intersection with GHb, if it extends this far, is expected at about 1115 m. GH is also expected to intersect some of the mine workings at the 410 m level, these locations can be deduced from the map in Figure 3.21. According to the interpretation given in Chapter 3 feature GH should intersect the access drifts to the 3D-migration drift and the Crosshole Site. This is also the case and the actual locations of the intersections of GH with the drifts at the 360 m level are shown in Figure 3.20. It should be noted that the dip of GH is uncertain and that a change of the interpreted dip will cause subsequent changes in the intersection of GH with the drifts. However, from the data it is clear that the dip of GH is "steep" which implies that changes in dip will only cause minor relocations of the intersections with the drifts at the 385 and 410 m levels.

In the W-boreholes GH contains breccia and mylonite and the granite is red colored. A similar appearance of the feature is expected at its other intersections with drifts. The width of GHa in the W-holes is 7-8 m and considering the relative orientation of GHa and the boreholes the actual width is estimated to be approximately 5 m. GHb is located about 15 m west of GHa but the extent of this parallel feature is uncertain.

Feature GC is expected to intersect the access drift 5-10 m west of the end face of the access drift where the D-boreholes will be drilled (Figure 3.21). GC is
a feature with a width of about 1-2 m. Hence it might be difficult to identify in the access drift.

6.3.3 C and D boreholes

The interpreted intersections of the major features with the C-boreholes are listed in Tables 6.1-6.4. The tables include data on the location of the intersection, error bounds and angle of intersection as would be obtained from single hole radar measurements in the new boreholes. The orientation of the major features as given in Chapter 3 is considered to have an accuracy of 5°. The error estimates of intersections given in Tables 6.1-6.4 are based on the assumption that a point on each plane is known. These are the centre points given in Tables 3.3-3.8. A change in the assumed orientation of 5° will move the intersection points with the new boreholes by a certain amount depending on the distance from the borehole to the centre point and the angle of intersection between the plane and the borehole.

The intersection of the major features with the new boreholes is expected to be associated with geophysical anomalies of the same magnitude as encountered in the "boundary boreholes". This implies normal resistivity values below 100 000 ohmm and seismic velocities below 6 000 m/s. The minor feature GC is expected to produce anomalies of smaller magnitude.

A prediction of the hydraulic conductivities likely to be encountered in the C boreholes has been made on the basis of where defined geophysical features are likely to intersect them.

The hydraulic conductivity of "average rock" was obtained by subtracting the transmissivity associated with distinct features from the overall results. This yielded a "background" of about $1 \times 10^{-9}$ m/s for the average rock (see Figure 6.6). Next the transmissivities of the major geophysical features were evaluated where they intersected existing N and W boreholes. A value for each zone was then devised based on the upper quartile of the transmissivity distribution for a particular feature. Since there were never more than 5 results for each feature this was a relatively arbitrary choice. The combined result of this prediction is given in Figure 6.6.
Table 6.1 Calculated intersections of major features with borehole C1.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Borehole intersection length</th>
<th>angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>117±8 m</td>
<td>58</td>
</tr>
<tr>
<td>GB</td>
<td>94±4 m</td>
<td>60</td>
</tr>
<tr>
<td>GC</td>
<td>30±7 m</td>
<td>58</td>
</tr>
<tr>
<td>GHa</td>
<td>45±3 m</td>
<td>81</td>
</tr>
<tr>
<td>GHb</td>
<td>56±3 m</td>
<td>81</td>
</tr>
<tr>
<td>GI</td>
<td>110±6 m</td>
<td>68</td>
</tr>
</tbody>
</table>

Table 6.2 Calculated intersections of major features with borehole C2.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Borehole intersection length</th>
<th>angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>103±2.5 m</td>
<td>75</td>
</tr>
<tr>
<td>GB</td>
<td>81±2 m</td>
<td>80</td>
</tr>
<tr>
<td>GC</td>
<td>25±7 m</td>
<td>75</td>
</tr>
<tr>
<td>GHa</td>
<td>54±5 m</td>
<td>56</td>
</tr>
<tr>
<td>GHb</td>
<td>67±6 m</td>
<td>56</td>
</tr>
<tr>
<td>GI</td>
<td>-</td>
<td>43</td>
</tr>
</tbody>
</table>

Table 6.3 Calculated intersections of major features with borehole C3.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Borehole intersection length</th>
<th>angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>-</td>
<td>45</td>
</tr>
<tr>
<td>GB</td>
<td>-</td>
<td>49</td>
</tr>
<tr>
<td>GC</td>
<td>39±9 m</td>
<td>45</td>
</tr>
<tr>
<td>GHa</td>
<td>50±1.5 m</td>
<td>64</td>
</tr>
<tr>
<td>GHb</td>
<td>62±1.5 m</td>
<td>64</td>
</tr>
<tr>
<td>GI</td>
<td>-</td>
<td>59</td>
</tr>
</tbody>
</table>
Table 6.4 Calculated intersections of major features with borehole D1.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Borehole intersection length</th>
<th>angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>-</td>
<td>35</td>
</tr>
<tr>
<td>GB</td>
<td>81±4 m</td>
<td>39</td>
</tr>
<tr>
<td>GC</td>
<td>-</td>
<td>35</td>
</tr>
<tr>
<td>GHa</td>
<td>21±4 m</td>
<td>56</td>
</tr>
<tr>
<td>GHb</td>
<td>34±4 m</td>
<td>56</td>
</tr>
<tr>
<td>GI</td>
<td>98±5 m</td>
<td>55</td>
</tr>
</tbody>
</table>

Figure 6.6 Prediction of hydraulic conductivity in the 3 boreholes C1, C2, and C3.
6.4 PREDICTION OF FRACTURE PATTERN FOR THE C AND D BOREHOLES

The C and D boreholes are drilled in new directions compared to the previous boreholes drilled as a part of the SCV Project. We have used the fracture data collected during Stage I to predict the fracture patterns that will be determined from the logging of the C and D boreholes.

The approach used to make these initial predictions is based on the empirical orientation bias corrections procedure presented by Terzaghi (1965). This approach has been applied by first correcting the data from those sections of the N and W boreholes that fall within the SCV block for the orientation bias that results from the orientation of the boreholes with respect to the fracture orientations. The contour plot of poles to fracture planes given in Figure 6.7 shows the full data set, within the block, corrected for orientation bias. Using this corrected data set, the orientation and number of fractures intersecting the projected length of the three C boreholes and the D boreholes have been computed (Figures 6.8 and 6.9). These contour plots of poles to fracture planes are a prediction of what the raw data plots for each borehole will look like before any corrections for orientation bias.
Figure 6.7 Contour plot of the poles to fracture planes for all boreholes within the SCV block boundaries. Additional fractures have been added to the data set to correct for orientation bias in the form of blind zones. Each dot represents the pole to a fracture plane. Contours are spaced 0.1 density units.
Figure 6.8 Predicted fracture geometry for (a) C1 and (b) C2. These plots are not corrected for orientation bias. The number of coated and sealed fractures for each borehole are given on each plot.
Figure 6.9 Predicted fracture geometry for (a) C3 and (b) D1. These plots are not corrected for orientation bias. The number of coated and sealed fractures for each borehole are given on each plot.
6.5 FRAMEWORK AND STRATEGY FOR PREDICTIVE MODELLING

Numerical modelling of fluid flow in both porous and fractured media requires well defined boundary conditions. The Stripa mine, as described earlier, forms a large sink that has a major impact on the local and regional flow system. It produces a major perturbation of the hydraulic heads in the vicinity of the mine as well as having a major controlling influence on the pathways that the groundwater follows in moving through the surrounding rock mass.

Since the major fracture zones have much higher porosity and permeability than the average fractured rock mass, and they can be discontinuous on both the scale of the mine and of the SCV area, their influence on the hydraulic heads within the SCV site depends in part on whether they intersect a boundary condition such as a mine opening. It is possible that a fracture zone may intersect the SCV block but still lie completely within the undisturbed rock mass. However, when the validation drift is completed it may penetrate the feature. In this case the measured hydraulic heads in the N and W boreholes would not be a very good prediction of the hydraulic head conditions on the boundary of the SCV block.

To determine the boundary conditions for the 3-D discrete fracture modelling of the validation drift area, we have started with the regional flow model and the sub-model of Gale et al (1987). From the sub-model we have developed an equivalent continuous porous media model (the mine model) of the eastern half of the mine. The surface plan view of this model is shown in Figure 6.10. The model consists of sixteen layers and five major fracture zones. The boundary conditions are interpolated from the sub-model results with all of the internal nodes located on mine openings and old mine stopes being assigned hydraulic heads equal to elevation heads.

The depth-permeability/porosity distribution used in the sub-model has also been used in the mine model. However, the hydraulic properties for the fracture zones for the layers in the SCV block are those measured during the borehole tests in the N and W boreholes. Also the anisotropic properties of the 3-D porous media elements representing the SCV block in the mine model will be determine by integrating the fracture and hydrology data from Stages I and III. The additional detail simulated in the mine model will probably require several iterations between the mine model and the sub-model before the boundary conditions for the 3-D discrete fracture model (block model) can be calculated. In addition, the mine
model will be used to calculate the average flow into the validation drift and the pathways followed by the groundwater moving into the validation drift from the surrounding rock mass.

The block model will include a volume of the rock mass surrounding the validation drift that is represented by a number of the 3-D elements within the porous media mine model. The major fracture zones will be included in the block model as a number of discrete features with specified properties. However, the regular fracture network will be generated from the statistics of fracture geometry - orientation, length, spacing and aperture. Due to the limits on computer storage we will either have to simulate a small volume of the rock mass and hence only a few of the elements within the 3-D model or else use only the tails of the fracture length and spacing distributions in simulating the fracture networks. The discrete model will enable us to predict the distribution of flux into the drift and the general pathways followed by a solute, for a number of simulations of the fracture network, taking into account the effects of stress and free-surface conditions in the larger fractures on flow in fracture systems.
Figure 6.10 Plan view of the "Mine model" finite element mesh for the 3-D porous media model that will be used to calculate the hydraulic head boundary conditions for the 3-D discrete fracture model. The thickness of each of the sixteen layers in the model are shown in the figure. Also, the area included in this model can be compared in the inset to its size in the sub-model region of Gale et. al. (1987). Note the location of the Ventilation and Z shafts, the validation (V) drift and the heavy lines marking the location of the fracture zones.
This report represents the results of the combined efforts of the research groups listed in Section 1.4. The authors are grateful for the commitment and enthusiasm shown by these groups during the execution of their various tasks and in providing material for this report. We also acknowledge the invaluable assistance provided by the personnel at the Stripa mine which has facilitated the collection of field data.

The valuable comments on the manuscript provided by the members of the Stripa Project Task Force on Fracture Flow Modelling are appreciated.


Stripa Project – Previously Published Reports

1980
TR 81-01
"Summary of defined programs"
L Carlsson and T Olsson
Geological Survey of Sweden, Uppsala
I Neretmeks
Royal Institute of Technology, Stockholm
R Pusch
University of Luleå
Sweden November 1980

IR 81-02
"Buffer Mass Test – Data Acquisition and Data Processing Systems"
B Hagvall
University of Luleå, Sweden August 1982

IR 81-03
"Buffer Mass Test – Software for the Data Acquisition System"
B Hagvall
University of Luleå, Sweden August 1982

IR 81-04
"Core-logs of the Subhorizontal Boreholes N1 and E1"
L Carlsson, V Stejskal
Royal Institute of Technology, Stockholm
T Olsson
K-Konsult, Engineers and Architects, Stockholm
Sweden August 1982

IR 81-05
"Core-logs of the Vertical Borehole V2"
L Carlsson, T Eggert, B Westlund
K-Konsult, Engineers and Architects, Stockholm
Sweden August 1982

IR 82-06
"Buffer Mass Test – Buffer Materials"
R Pusch, L Borgesson
University of Luleå
J Nilsson
AB Jacobson & Widmark, Luleå
Sweden August 1982

IR 82-07
"Buffer Mass Test – Rock Drilling and Civil Engineering"
R Pusch
University of Luleå
J Nilsson
AB Jacobson & Widmark, Luleå
Sweden September 1982

1981
TR 81-01
"Annual Report 1980"
Swedish Nuclear Fuel Supply Co/Division KBS
Stockholm, Sweden 1981

IR 82-02
"Annual Report 1981"
Swedish Nuclear Fuel Supply Co/Division KBS
Stockholm, Sweden February 1982

IR 82-03
"Migration in a single fracture Preliminary experiments in Stripa"
Harald Abelin, Ivars Neretmeks
Royal Institute of Technology, Stockholm
Sweden April 1981

IR 82-04
"Equipment for hydraulic testing"
Lars Jacobsson, Henrik Norlander
Ställbergs Grufve AB
Stripa, Sweden July 1981

IR 82-05
Part I "Core-logs of borehole VI down to 505 m"
L Carlsson, V Stejskal
Geological Survey of Sweden, Uppsala
T Olsson
K-Konsult, Stockholm

Part II "Measurement of Triaxial rock stresses in borehole VI"
L Strindell, M Andersson
Swedish State Power Board, Stockholm
Sweden July 1981

IR 82-06
"Buffer Mass Test – Buffer Materials"
R Pusch, L Borgesson
University of Luleå
J Nilsson
AB Jacobson & Widmark, Luleå
Sweden August 1982
IR 82-08
"Buffer Mass Test – Predictions of the behaviour of the bentonite-based buffer materials"
L Borgesson
University of Luleå
Sweden August 1982

1983
IR 83-01
"Geochemical and isotope characterization of the Stripa groundwaters – Progress report"
Leif Carlsson,
Swedish Geological, Göteborg
Tommy Olsson,
Geological Survey of Sweden, Uppsala
John Andrews,
University of Bath, UK
Jean-Charles Fontes,
Université, Paris-Sud, Paris, France
Jean L Michelot,
Université, Paris-Sud, Paris, France
Kirk Nordstrom,
United states Geological Survey, Menlo Park
California, USA
February 1983

TR 83-02
"Annual Report 1982"
Swedish Nuclear Fuel Supply Co/ Division KBS
Stockholm, Sweden April 1983

IR 83-03
"Buffer Mass Test – Thermal calculations for the high temperature test"
Sven Knutsson
University of Luleå
Sweden May 1983

IR 83-04
"Buffer Mass Test – Site Documentation"
Roland Pusch
University of Luleå and Swedish State Power Board
Jan Nilsson
AB Jacobson & Widmark, Luleå.
Sweden October 1983

IR 83-05
"Buffer Mass Test – Improved Models for Water Uptake and Redistribution in the Heater Holes and Tunnel Backfill"
R Pusch
Swedish State Power Board
L Borgesson, S Knutsson
University of Luleå
Sweden, October 1983

IR 83-06
"Crosshole Investigations — The Use of Borehole Radar for the Detection of Fracture Zones in Crystalline Rock"
Olle Olsson
Erik Sandberg
Swedish Geological
Bruno Nilsson
Boliden Mineral AB, Sweden
October 1983

1984
TR 84-01
"Annual Report 1983"
Swedish Nuclear Fuel Supply Co/Division KBS

IR 84-02
"Buffer Mass Test — Heater Design and Operation"
Jan Nilsson
Swedish Geological Co
Gunnar Ramqvist
E-tekn AB
Roland Pusch
Swedish State Power Board
June 1984

IR 84-03
"Hydrogeological and Hydrogeochemical Investigations — Geophysical Borehole Measurements"
Olle Olsson
Ante Jämtlid
Swedish Geological Co.
August 1984

IR 84-04
"Crosshole Investigations — Preliminary Design of a New Borehole Radar System"
O. Olsson
E. Sandberg
Swedish Geological Co.
August 1984

IR 84-05
"Crosshole Investigations — Equipment Design Considerations for Sinusoidal Pressure Tests"
David C. Holmes
British Geological Survey
September 1984
IR 84-06
“Buffer Mass Test — Instrumentation”
Roland Pusch, Thomas Forsberg
University of Luleå, Sweden
Jan Nilsson
Swedish Geological, Luleå
Gunnar Ramqvist, Sven-Erik Tegelmark
Stripa Mine Service, Storå
September 1984

IR 84-07
“Hydrogeological and Hydrogeochemical”
Investigations in Boreholes — Fluid
Inclusion Studies in the Stripa Granite
Sten Lindblom
Stockholm University, Sweden
October 1984

IR 84-08
“Crosshole Investigations — Tomography and its Application to Crosshole Seismic Measurements”
Sven Ivansson
National Defence Research Institute, Sweden
November 1984

1985
IR 85-01
“Borehole and Shaft Sealing — Site documentation”
Roland Pusch
Jan Nilsson
Swedish Geological Co
Gunnar Ramqvist
Eltekn AB
Sweden
February 1985

IR 85-02
“Migration in a Single Fracture — Instrumentation and site description”
Harald Abelin
Jard Gidlund
Royal Institute of Technology
Stockholm, Sweden
February 1985

TR 85-03
“Final Report of the Migration in a Single Fracture — Experimental results and evaluation”
H. Abelin
I. Neretnieks
S. Tunbrant
L. Moreno
Royal Institute of Technology
Stockholm, Sweden
May 1985

IR 85-04
“Hydrogeological and Hydrogeochemical Investigations in Boreholes — Compilation of geological data”
Seje Carlsten
Swedish Geological Co
Uppsala, Sweden
June 1985

IR 85-05
“Crosshole Investigations — Description of the small scale site”
Seje Carlsten
Kurt-Åke Magnusson
Olle Olsson
Swedish Geological Co
Uppsala, Sweden
June 1985

TR 85-06
“Hydrogeological and Hydrogeochemical Investigations in Boreholes — Final report of the phase I geochemical investigations of the Stripa groundwaters”
D.K. Nordstrom, US Geological Survey, USA
J.N. Andrews, University of Bath, United Kingdom
L. Carlsson, Swedish Geological Co, Sweden
J-C. Fontes, Universite Paris-Sud, France
P. Fritz, University of Waterloo, Canada
H. Moser, Gesellschaft für Strahlen- und Umweltforschung, West Germany
T. Olsson, Geosystem AB, Sweden
July 1985

TR 85-07
“Annual Report 1984”
Swedish Nuclear Fuel and Waste Management Co.
Stockholm, July 1985

IR 85-08
“Hydrogeological and Hydrogeochemical Investigations in Boreholes—Shut-in tests”
L. Carlsson
Swedish Geological Co
T. Olsson
Uppsala Geosystem AB
July 1985

IR 85-09
“Hydrogeological and Hydrogeochemical Investigations in Boreholes—Injection-recovery tests and interference tests”
L. Carlsson
Swedish Geological Co
T. Olsson
Uppsala Geosystem AB
July 1985
TR 85-10
“Hydrogeological and Hydrogeochemical Investigations in Boreholes—Final report”
L. Carlsson
Swedish Geological Co
T. Olsson
Uppsala Geosystem AB
July 1985

TR 85-11
“Final Report of the Buffer Mass Test—Volume I: scope, preparative field work, and test arrangement”
R. Pusch
Swedish Geological Co, Sweden
J. Nilsson
Swedish Geological Co, Sweden
G. Ramqvist
El-teknko Co, Sweden
July 1985

TR 85-12
R. Pusch
Swedish Geological Co, Sweden
L. Börgesson
Swedish Geological Co, Sweden
G. Ramqvist, El-teknko Co, Sweden
August 1985

IR 85-13
“Crosshole Investigations — Compilation of core log data from F1-F6”
S. Carlsten.
A. Stråhle.
Swedish Geological Co, Sweden
September 1985

TR 85-14
Roland Pusch
Swedish Geological Co.
Sweden
November 1995

1986
IR 86-01
“Crosshole Investigations — Description of the large scale site”
Göran Nilsson
Olle Olsson
Swedish Geological Co, Sweden
February 1986

IR 86-02
“Hydrogeological Characterization of the Ventilation Drift (Buffer Mass Test) Area, Stripa, Sweden”
J.E. Gale
Memorial University, Nfld., Canada
A. Rouleau
Environment Canada, Ottawa, Canada
February 1986

IR 86-03
“Crosshole Investigations — The method, theory and analysis of crosshole sinusoidal pressure tests in fissured rock”
John H Black
John A Barker*
David J. Noy
British Geological Survey, Keyworth, Nottingham, United Kingdom
Wallingford, Oxon. United Kingdom
June 1986

TR 86-04
“Executive Summary of Phase 1”
Swedish Nuclear Fuel and Waste Management Co.
Stockholm, July 1986

TR 86-05
“Annual Report 1985”
Swedish Nuclear Fuel and Waste Management Co.
Stockholm, August 1986
1987
TR 87-01
"Final Report of the Borehole, Shaft, and Tunnel Sealing Test — Volume I: Borehole plugging"
R. Pusch
L. Börgesson
Swedish Geological Co., Sweden
G. Ramqvist
El-Tekno Co., Sweden
January 1987

TR 87-02
"Final Report of the Borehole, Shaft, and Tunnel Sealing Test — Volume II: Shaft plugging"
R. Pusch
L. Börgesson
Swedish Geological Co., Sweden
G. Ramqvist
El-Tekno Co., Sweden
January 1987

TR 87-03
"Final Report of the Borehole, Shaft, and Tunnel Sealing Test — Volume III: Tunnel plugging"
R. Pusch
L. Börgesson
Swedish Geological Co., Sweden
G. Ramqvist
El-Tekno Co., Sweden
February 1987

TR 87-04
"Crosshole Investigations — Details of the Construction and Operation of the Hydraulic Testing System"
D. Holmes
British Geological Survey, United Kingdom
M. Sehlstedt
Swedish Geological Co., Sweden
May 1986

IR 87-05
"Workshop on Sealing Techniques, tested in the Strips Project and being of General Potential use for Rock Sealing"
R. Pusch
Swedish Geological Co., Sweden
February 1987

TR 87-06
"Crosshole Investigations — Results from Seismic Borehole Tomography"
J. Pihl
M. Hammarström
S. Ivansson
P. Morén
National Defence Research Institute, Sweden
December 1986

TR 87-07
"Reflection and Tubewave Analysis of the Seismic Data from the Strips Crosshole Site"
C. Cosma
Vibrometric OY, Finland
S. Bähler
M. Hammarström
J. Pihl
National Defence Research Institute, Sweden
December 1986

TR 87-08
"Crosshole Investigations — Short and Medium Range Seismic Tomography"
C. Cosma
Vibrometric OY, Finland
February 1987

TR 87-09
"Program for the Strips Project Phase 3, 1986—1991"

TR 87-10
"Crosshole Investigations — Physical Properties of Core Samples from Boreholes F1 and F2"
K.-Å. Magnusson
S. Carlsten
C. Olsson
Swedish Geological Co., Sweden
June 1987
TR 87-11
"Crosshole Investigations—Results from Borehole Radar Investigations"
O Olsson, L Falk, O Forslund, L Lundmark, E Sandberg
Swedish Geological Co. Sweden
May 1987

TR 87-12
Swedish Nuclear Fuel and Waste Management Co, Stockholm
June 1987

TR 87-13
"Rock Stress Measurements in Borehole V3"
B. Bjarnason
G. Raillard
University of Luleå, Sweden
July 1987

TR 87-14
"Annual Report 1986"
August 1987

TR 87-15
"Hydrogeological Characterization of the Stripa Site"
J. Gale
R. Macleod
J. Welhan
Memorial University, Nfld., Canada
C. Cole
L. Vail
Battelle Pacific Northwest Lab.
Richland, Wash., USA
June 1987

TR 87-16
"Crosshole Investigations — Final Report"
O. Olsson
Swedish Geological Co, Sweden
J. Black
British Geological Survey, United Kingdom
C. Cosma
Vibrometric OY, Finland
J. Phil
National Defence Research Institute, Sweden
September 1987

TR 87-17
"Site Characterization and Validation — Geophysical Single Hole Logging"
B. Fridh
Swedish Geological Co, Sweden
December 1987

TR 87-18
"Crosshole Investigations — Hydrogeological Results and Interpretations"
J. Black
D. Holmes
M. Brightman
British Geological Survey, United Kingdom
December 1987

TR 87-19
"3-D Migration Experiment — Report 1
Site Preparation and Documentation"
H. Abelin
L. Birgersson
Royal Institute of Technology, Sweden
November 1987

TR 87-20
"3-D Migration Experiment — Report 2
Instrumentation and Tracers"
H. Abelin
L. Birgersson
J. Gidlund
Royal Institute of Technology, Sweden
November 1987

TR 87-21
Part I "3-D Migration Experiment — Report 3
Performed Experiments, Results and Evaluation"
H. Abelin
L. Birgersson
J. Gidlund
L. Moreno
I. Neretnieks
H. Widen
T. Agren
Royal Institute of Technology, Sweden
November 1987

Part II "3-D Migration Experiment — Report 3
Performed Experiments, Results and Evaluations Appendices 15, 16 and 17"
H. Abelin
L. Birgersson
J. Gidlund
L. Moreno
I. Neretnieks
H. Widen
T. Agren
Royal Institute of Technology, Sweden
November 1987
TR 87-22
“3-D Migration Experiment — Report 4
Fracture Network Modelling of the Stripa 3-D Site”
J. Andersson
B. Dverstorp
Royal Institute of Technology, Sweden
November 1987

1988
TR 88-01
“Crosshole Investigations — Implementation and Fractional Dimension Interpretation of Sinusoidal Tests”
D. Noy
J. Barker
J. Black
D. Holmes
British Geological Survey, United Kingdom
February 1988

IR 88-02
“Site Characterization and Validation — Monitoring of Head in the Stripa Mine During 1987”
S. Carlsten
O. Olsson
O. Persson
M. Sehistedt
Swedish Geological Co., Sweden
April 1988

TR 88-03
“Site Characterization and Validation — Borehole Rodar Investigations, Stage I”
O. Olsson
J. Eriksson
L. Falk
E. Sandberg
Swedish Geological Co., Sweden
April 1988

TR 88-04
“Rock Sealing — Large Scale Field Test and Accessory Investigations”
R. Pusch
Clay Technology, Sweden
March 1988

TR 88-05
“Hydrogeochemical Assessment of Crystalline Rock for Radioactive Waste Disposa The Stripa Experience”
J. Andrews
University of Bath, United Kingdom
J-C. Fontes
Université Paris-Sud, France
P. Fritz
University of Waterloo, Canada
K. Nordstrom
US Geological Survey, USA
August 1988

TR 88-06
“Annual Report 1987”
June 1988

IR 88-07
“Site Characterization and Validation — Results From Seismic Crosshole and Reflection Measurements, Stage I”
C. Cosma
R. Korhonen
Vibrometric Oy, Finland
M. Hammarström
P. Morén
J. Pihl
National Defence Research Institute, Sweden
September 1988

IR 88-08
“Stage I Joint Characterization and Stage II Preliminary Prediction using Small Core Samples”
G. Vik
N. Barton
Norwegian Geotechnical Institute, Norway
August 1988

IR 88-09
“Site Characterization and Validation — Hydrochemical Investigations in Stage I”
P. Wikberg
M. Laaksoharju
J. Bruno
A. Sandino
Royal Institute of Technology, Sweden
September 1988
IR 88-10
"Site Characterization and Validation – Drift and Borehole Fracture Data Stage I"
J. Gale
Freeflow Consultants Inc., Nfld., Canada
A. Stråhle
Swedish Geological Co, Uppsala, Sweden
September 1988

TR 88-11
"Rock Sealing – Interim Report on the Rock Sealing Project (Stage I)"
R. Pusch
L. Börgesson
A. Fredrikson
Clay Technology, Sweden
I. Markström
M. Erlström
Swedish Geological Co, Sweden
G. Ramqvist
El-Tekno AB, Sweden
M. Gray
AECL, Canada
W. Coons
IT Corp., USA
September 1988

1989
TR 89-01
"Executive Summary of Phase 2"
Swedish Nuclear Fuel and Waste Management Co.,
Stockholm
February 1989

TR 89-02
"Fracture Flow Code Cross – Verification Plan"
W. Dershowitz
Golder Associates Inc., USA
A. Herbert
AEPE Harwell Laboratory, U. K.
J. Long
Lawrence Berkeley Laboratory, USA
March 1989