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TECHNICAL REPORT 87-35

CROSSHOLE INVESTIGATIONS – FINAL REPORT

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SWEDEN

SEPTEMBER 1987

Parkstrasse 23 5401 Baden/Schweiz Telephon 056/20 55 11

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

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

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

Das Stripa-Projekt ist ein Projekt der Nuklearagentur der OECD. Unter internationaler Beteiligung werden von 1980-86 Forschungsarbeiten in einem unterirdischen Felslabor in Schweden durchgeführt. Diese sollen die Kenntnisse auf folgenden Gebieten erweitern:

- hydrogeologische und geochemische Messungen in Bohrlöchern
- Ausbreitung des Grundwassers und Transport von Radionukliden durch Klüfte im Gestein
- Verhalten von Materialien, welche zur Verfüllung und Versiegelung von Endlagern eingesetzt werden sollen
- Methoden zur zerstörungsfreien Ortung von Störzonen im Fels

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

The Stripa Project is organised as an autonomous project of the Nuclear Energy Agency of the OECD. In the period from 1980-86, an international cooperative programme of investigations is beeing carried out in an underground rock laboratory in Sweden. The aim of the work is to improve our knowledge in the following areas:

- hydrogeological and geochemical measurement methods in boreholes
- flow of groundwater and transport of radionuclides in fissured rock
- behaviour of backfilling and sealing materials in a real geological environment
- non-destructive methods for location of disturbed zones in the rock

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

Le projet Stripa est un projet autonome de l'Agence de l'OCDE pour l'Energie Nucléaire. Il s'agit d'un programme de recherche avec participation internationale, qui sera réalisé entre 1980 et 1986 dans un laboratoire souterrain, en Suède. Le but de ces travaux est d'améliorer et d'étendre les connaissances dans les domaines suivants:

- mesures hydrogéologiques et géochimiques dans les puits de forage
- chimie des eaux souterraines à grande profondeur
- écoulement des eaux souterraines et transport des radionucléides dans les roches fracturées
- comportement des matériaux de colmatage et de scellement des dépôts finals
- méthodes de localisation non destructive des zones de perturbation de la roche

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

ABSTRACT

The Crosshole programme has comprised the development of borehole radar, borehole seismic, and hydraulic testing methods. These methods provide data on the electric, elastic, and hydraulic properties of the rock. For each of these methods new equipment has been developed, field tests have been performed, interpretation techniques developed and tested on the obtained data. Finally, a comparison of the results obtained with the different methods has been made.

During the course of the Crosshole project the radar and seismic methods have been taken from the prototype stage into being practical site characterization tools.

The analysis of the radar and seismic data has given a consistent description of the fracture zones at the Crosshole site in agreement with geological and other geophysical observations made in the boreholes. The geophyscal methods have achieved a resolution of a few metres combined with probing ranges of a few hundred metres.

The hydraulic investigations within the Crosshole project have yielded substantial progress in assessing the hydrogeology of fractured granitic rocks. The crosshole hydraulic testing concentrated on measuring the distribution of hydraulic properties within the extensive fractured zones identified by geophysics. An approach was adopted based on a sinusoidally varying pressure and flow rate to minimize testing time and to allow the signal to be observed against a changing background.

A new analysis involving the "dimension" of the flow test has been developed to analyse the results of the crosshole sinusoidal testing. This is a versatile analysis well-suited to the sort of flow geometries likely to be found in crystalline rocks.

The combined analysis of the geophysical and the hydraulic data set has shown that groundwater flow is concentrated within a few major features which have been identified by the geophysical methods. The main features are considered to be broadly planar, containing patches of high and low hydraulic conductivity. The fracture zones are likely to be channelled, where the flow paths constitute a branching interconnecting network.

RESUME

Les méthodes de radar, de sismique et d'hydraulique de forage ont été perfectionnées dans le cadre du programme entre puits. Elles procurent des données sur les caractéristiques électriques, élastiques et hydrauliques de la roche. On a mis au point de nouveaux instruments pour chacune de ces méthodes de recherches, réalisé des études sur le terrain, amélioré les techniques d'interprétation et testé les résultats obtenus avec les données disponibles. On a enfin procédé à la comparaison des résultats obtenus avec les différentes méthodes.

Au cours du projet entre puits, on a développé des techniques prototypes de radar et de sismique, afin de pouvoir les utiliser de manière routinière pour la caractérisation de site.

L'analyse des données radar et sismiques a permis de déterminer la position des zones de fractures sur le site entre puits; il se trouve qu'elle concorde avec les résultats des observations géologiques et géophysiques faites dans les puits de forage. Les méthodes géophysiques ont atteint une résolution de quelques mètres pour un rayon d'action de quelques centaines de mètres.

Les investigations hydrauliques réalisées dans le cadre du projet entre puits ont considérablement progressé en ce qui concerne l'appréciation de l'hydrogéologie de la roche granitique fracturée. Ces recherches ont essentiellement porté sur la répartition des propriétés hydrauliques à l'intérieur des zones de fractures étendues, que des méthodes géophysiques avaient identifiées. Pour réduire le plus possible la durée de test et pouvoir observer le signal, également avec des conditions d'arrière fond changeantes, on a adopté une méthode d'essais au cours de laquelle on a fait varier de manière sinusoïdale la pression et le taux d'écoulement.

On a mis au point une nouvelle méthode d'analyse comprenant la "dimension" de l'écoulement, afin d'analyser les résultats du test entre puits avec signaux sinusoïdaux. Cette méthode d'analyse variée s'est avérée convenir aux géométries d'écoulement que l'on peut rencontrer dans les roches cristallines.

L'analyse combinée des données géophysiques et hydrauliques a montré que l'écoulement des eaux souterraines se concentre sur quelques rares zones de perturbations, que des méthodes géophysiques ont permis d'identifier. Les principales zones de perturbations semblent être largement planaires et montrent par endroits des conductibilités hydrauliques plus élevées et plus basses. Les zones de fractures comportent probablement des canaux, les voies d'écoulement étant constituées d'un réseau ramifié continu de ces canaux.

ZUSAMMENFASSUNG

Im Rahmen des Crosshole-Programms wurden die Verfahren des Bohrlochradars, der Bohrlochseismik und der Bohrlochhydraulik weiterentwickelt. Diese Untersuchungsmethoden liefern Daten über die elektrischen, elastischen und hydraulischen Eigenschaften des Gesteins. Für jede Methode wurden neue Instrumente entwickelt, Felduntersuchungen durchgeführt und Auswertungsverfahren verbessert sowie die Resultate mit den vorhandenen Daten getestet. Zuletzt wurden die Ergebnisse der verschiedenen Methoden miteinander verglichen.

Während des Projektes wurden die Prototyp-Radar- und Seismik-Techniken soweit entwickelt, dass sie routinemässig zur Standortcharakterisierung eingesetzt werden können.

Die Analyse der Radar- und seismischen Daten ergab eine Lagebestimmung der Kluftzonen des Crosshole-Standortes, die eine gute Übereinstimmung mit den Ergebnissen der in den Bohrlöchern durchgeführten geologischen und geophysikalischen Beobachtungen zeigte. Die geophysikalischen Methoden haben eine Auflösung von einigen Metern bei Reichweiten von einigen hundert Metern erreicht.

Die hydraulischen Untersuchungen des Crosshole-Projektes haben beträchtliche Fortschritte in der Beurteilung der Hydrogeologie von geklüftetem granitischem Gestein gemacht. Die Untersuchungen haben sich vor allem mit der Verteilung von hydraulischen Eigenschaften innerhalb der ausgedehnten Kluftzonen befasst, die durch geophysikalische Methoden identifiziert werden konnten. Um die Testdauer auf ein Minimum zu reduzieren und das Signal auch bei sich ändernden Hintergrundbedingungen beobachten zu können, wurde eine Testmethode angewandt, bei der Druck und Fliessrate sinusförmig variiert wurden.

Eine neue Analysemethode, welche die "Dimension" des Flusses einbezieht, wurde entwickelt, um die Resultate des Crosshole-Tests mit sinusförmigen Signalen zu analysieren. Dieses vielseitige Analyseverfahren hat sich als geeignet für die in kristallinen Gesteinen vorkommenden Fliessgeometrien erwiesen.

Die kombinierte Analyse der geophysikalischen und hydraulischen Datensätze hat gezeigt, dass der Grundwasserfluss auf wenige grössere Störungszonen konzentriert ist, die durch geophysikalische Methoden identifiziert werden konnten. Die Hauptstörzonen scheinen weitgehend planar zu sein und zeigen stellenweise höhere und tiefere hydraulische Leitfähigkeiten. Die Kluftzonen enthalten wahrscheinlich Kanäle, wobei die Fliesswege aus einem verästelten zusammenhängenden Netzwerk dieser Kanäle bestehen.

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SUMMARY

The Crosshole programme has comprised the development of borehole radar, borehole seismic, and hydraulic testing methods. These methods provide data on the electric, elastic, and hydraulic properties of the rock. For each of these methods new equipment has been developed, field tests have been performed, interpretation techniques developed and tested on the obtained data. Finally, the results obtained with the different methods have been compared.

A new borehole radar system has been developed. The system can be used in three different measurement modes; singlehole reflection, crosshole reflection, and crosshole tomography. The radar uses frequencies in the range 20 to 60 MHz, corresponding to wavelengths of 6 to 2 m. The radar has given data on the location, extent and properties of fracture zones with a resolution of a few metres. The probing ranges obtained have been approximately 100 m in the singlehole mode and 200 to 300 m in the crosshole mode.

The seismic method has mainly been interpreted using tomographic inversion. In this context a new iterative inversion technique has been developed which results in shorter computing times, especially for large data sets, than other iterative inversion methods. An important insight gained during the project is the high quality of data required to obtain tomograms which adequately represent the geology. Techniques for quality control and error correction have been devised and successfully implemented.

The analysis of the radar and seismic data has given a consistent description of the fracture zones at the Crosshole site. The seismic and radar anomalies appear in the same locations and the anomalies obtained from intersecting planes appear at the same location at intersections. Additionally the description is in agreement with geological and other geophysical observations made in the boreholes.

During the course of the Crosshole project the radar and seismic methods have been taken from the prototype stage into being practical site characterization tools.

The hydraulic investigations within the Crosshole project have yielded substantial progress in assessing the hydrogeology of fractured granitic rocks. This has resulted from improvements

concerning three aspects of hydraulic testing. Firstly the approach to testing has been improved by planning based on reliable geometric information about the whole region to be tested. Secondly the instrumentation used in the testing was computer based resulting in better adherence to interpretation assumptions and improved control over test conditions. Thirdly the testing has demonstrated the application of an improved and feasible interpretation concept which is more appropriate to fractured rocks than previous concepts derived from sedimentary rocks.

The crosshole hydraulic testing concentrated on measuring the distribution of hydraulic properties within the extensive fractured zones identified by geophysics. An approach was adopted based on sinusoidally varying pressure and flow rate to minimize time required for test zones to regain their pretesting head. The sinusoidal approach also allowed the signal to be observed against a changing background. The minimization of head disturbances during testing was also applied to the single-hole testing with a subsequent reduction in testing times.

The sinusoidal signal was generated by computer-based equipment which controlled the variation of pressure both outside the test zone as well as within it. This allowed good adherence to the assumptions of the test analysis and provided a measure of the leakage around the packers. The computer control also allowed the use of differential pressure transducers giving greater accuracy.

A new analysis involving the "dimension" of the flow test has been developed to analyse the results of the crosshole sinusoidal testing. This is a versatile analysis well-suited to the sort of flow geometries likely to be found in crystalline rocks.

The combined analysis of the geophysical and the hydraulic data set has showed that groundwater flow is concentrated within a few major features which have been identified by the geophysical methods. The main features are considered to be broadly planar, containing patches of high and low hydraulic conductivity. The fracture zones are likely to be channelled, where the flow paths constitute a branching interconnecting network.

1 INTRODUCTION

1.1 OBJECTIVES

The rock mass surrounding a nuclear waste repository is an essential barrier in preventing hazardous amounts of radioactive nuclides reaching the biosphere. The major forseeable mechanism for transporting any radionuclides from the waste will be within flowing groundwater. In crystalline rock essentially all groundwater transport takes place in fractures and fracture zones. Hence, the location of fracture zones and their transport capacity is fundamental to a quantitative description of radionuclide transport from a repository to the biosphere.

The objective of the Crosshole Program was to develop methods which could yield information on the suitability of a rock mass for final disposal of radioactive wastes. An important criterion was that the methods employed should be nondestructive, i.e. an investigation should only require a few boreholes. The main reason for limiting the number of holes during a site investigation is that the investigation holes themselves might provide significant transport paths for the groundwater. In the development of the investigation methods, effort has concentrated on the identification and characterization of fracture zones, which are considered to be the most important transport paths. A detailed study of the presence, character, and transport capacity of individual fractures has not been within the scope of the current program.

1.2 SCOPE OF WORK

The Crosshole Program has comprised the development of borehole radar, borehole seismic, and hydraulic testing methods. These methods provide data on the electric, elastic and hydraulic properties of the rock, respectively. For each of these methods new equipment has been developed, field tests have been performed, interpretation techniques have been developed and tested on the obtained data. The capability of these methods to describe the rock has been tested at a specially prepared site in the

Stripa Mine named the Crosshole Site. This site has been surveyed with a comprehensive set of singlehole methods to provide a frame of reference to which the crosshole methods could be compared. The site was designed to allow the methods to be tested at various scales in order to study their achievable resolution and range. The three methods have been applied at the same site to provide a comprehensive data set. This has facilitated a careful comparison of the results obtained by the different methods and the construction of a three dimensional model of the site.

At the start of this project, the borehole radar and seismic methods were novel techniques in applications related to crystalline rock. The methods are interesting in that they use wave propagation effects to obtain information about the structure of the rock. Such methods can provide a superior resolution compared to conventional methods which normally utilize some potential field effect (e.g. electric, magnetic or gravitational fields) to get information about the rock. The radar and seismic methods can be seen as remote sensing methods which provide high resolution combined with ranges of hundreds of meters. For both methods information about the rock has been obtained through the study of reflections and tomographic inversion of crosshole data.

The purpose of the hydraulic investigations were to provide a basis for calibrating the geophysical properties measured by radar and seismics with hydraulic properties relevant to repository siting. The hydraulic investigations also comprised the development of the sinusoidal testing technique. This novel technique facilitates crosshole hydraulic testing in a mine environment with rapidly changing heads and has the potential to examine fissure-water interactions.

The application of these methods at a common site and the integrated evaluation of the resulting data have provided a detailed description in three dimensions of the physical and hydraulic properties at the site. The large amounts of data of different types and on different scales have provided the means to describe the site with a resolution and confidence that is hardly reached elsewhere.

1.3 ORGANIZATION OF WORK

The Crosshole Program has been divided into three different subprogrammes, one for each method. The subprogrammes have been carried out by research groups from four different organizations:

- Borehole radar: Swedish Geological Co., Sweden.
- Borehole seismics: Swedish National Defence Research Institute (FOA), Sweden and Vibrometric OY, Finland.
- Hydraulics: British Geological Survey, United Kingdom.

Each technique has been developed individually but the planning of the experimental efforts and the interpretation of the results has been carried out jointly. The exchange of data and its integrated analysis has yielded a joint understanding of the results and their implications for nuclide transport through crystalline rock. The subprojects have thus been directed towards those goals which have provided the most benefit to the Crosshole Program as a whole.

In addition to the development of the three techniques there has also been an initial phase of site preparation and characterization. This has comprised the drilling of the six boreholes at the Crosshole Site and a detailed description of the cores and analysis of the geophysical singlehole logging results.

1.4 REPORTING OF RESULTS

The activities and results from the entire Crosshole Program are presented in this report. Following the description of the experimental site at the Stripa Mine the activities and the main results of each subproject are presented. The combined interpretation of the data from the Crosshole Site and the resulting model of the site is then presented followed by a discussion of the results of the Crosshole Program. The results have implications for site investigation programs in the future and concepts of water flow through fractured crystalline rock.

The results of the subprogrammes are presented in the following reports:

Site characterization

Carlsten, S., Magnusson, K.-Å., Olsson, O., Crosshole investigations - Description of the small scale site. IR 85-05.

Carlsten, S., Stråhle, A., Crosshole investigations - Compilation of core log data from F1-F6. IR 85-13.

Nilsson, G., Olsson, O., Crosshole investigations - Description of the large scale site. IR 86-01.

Borehole radar

Olsson, O., Sandberg, E., Nilsson, B., Crosshole investigations - The use of borehole radar for the detection of fracture zones in crystalline rock. IR 83-06.

Olsson, O., Sandberg, E., Crosshole investigations - Preliminary design of a new borehole radar system. IR 84-04.

Magnusson, K.-Å., Carlsten, S., Olsson, O., Crosshole investigations - Physical properties of core samples from boreholes F1 and F2. TR 87-10.

Olsson, O., Falk, L., Forslund, O., Lundmark, L., Sandberg, E., Crosshole investigations - Results from borehole radar investigations. TR 87-11.

Borehole seismics

Ivansson, S., Crosshole investigations - Tomography and its application to crosshole seismic measurements. IR 84-08.

Pihl, J., Hammarström, M., Ivansson, S., Moren, P., Crosshole investigations - Results from seismic borehole tomography. TR 87-06.

Cosma, C., Crosshole investigations - Short and medium range seismic tomography. TR 87-08.

Cosma, C., Bähler, S., Hammarström, M., Pihl, J., Crosshole investigations - Reflection and tube wave analysis of the seismic data from the Stripa Crosshole site. TR 87-07.

Hydraulics

Holmes, D. C., Crosshole investigations - Equipment design considerations for sinusoidal pressure tests. IR 84-05.

Black, J. H., Barker, J. A., Noy, D. J., Crosshole investigations - The method, theory and analysis of crosshole sinusoidal pressure tests in fissured rock. IR 86-03.

Holmes, D. C., Sehlstedt, M., Crosshole investigations - Details of the construction and operation of the hydraulic testing system. TR 87-04.

Noy, D. J., Barker, J. A., Crosshole investigations - The fractional dimension approach to the interpretation of sinusoidal tests in fissured rock. TR 87- .

Black, J. H., Holmes, D. C., Brightman, M. A., Crosshole investigations - Hydrogeological results and interpretation. TR 87- .

2 EXPERIMENTAL SITE

2.1 BOREHOLE CONFIGURATION

The bulk of the experimental activities made within the Crosshole Program have been performed at a specially prepared site in the Stripa Mine. The site is situated at the end of a drift at the 360 m level (Figure 2.1). Six boreholes have been drilled from the end of the drift in a fanlike fashion. The boreholes outline a tilted pyramid with a height and a base of about 200 m where all boreholes start from the top of the pyramid. With this borehole configuration the relative position of observation points is determined by the angles between the holes and hence the geometrical configuration is length invariant.

A perspective view of the borehole layout is shown in Figure 2.2. The boreholes can be grouped into two "fans" of boreholes. The "top fan" contains the boreholes named F1, F3, and F5 which are 200 m in length and have a dip of 10 degrees. The "bottom fan" contains the boreholes F2, F4, and F6 which are 250 m in length and have dips of 20, 30, and 40 degrees, respectively. Another symmetry within this system of boreholes is that F2 lies vertically beneath F1, F4 beneath F3, and F6 beneath F5. The The exact location, length and direction of the boreholes are listed in Table 2.1. An old investigation drift located at the 410 m level passes just below and close to the ends of the semi-horizontal boreholes F1, F3, and F5. This drift is air filled as it is just above the pumping level of the mine.

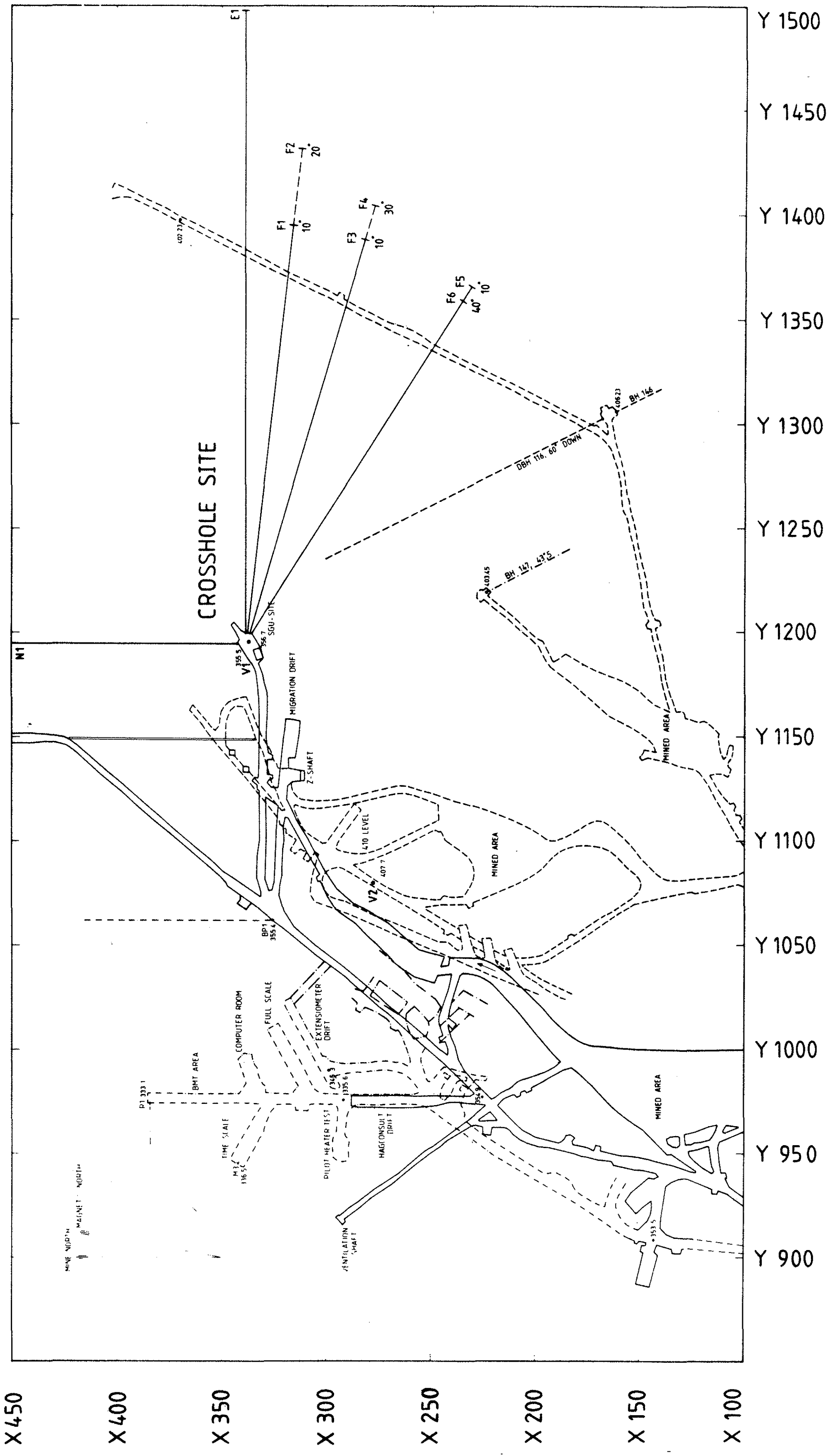


Figure 2.1 Plan view of the Stripa mine at the 360 m and 410 m levels showing the position of the Crosshole site with the boreholes F1 to F6.

Table 2.1. Position of boreholes F1-F6, in the local mine coordinates, declination from mine north (in degrees), inclination below horizontal plane (in degrees), and length (m).

Bore-hole	X	Y	Z	Decl.	Incl.	Length
F1	337.454	1199.291	355.437	96.25	10.20	200.10
F2	337.450	1199.242	355.895	95.86	20.57	249.88
F3	336.508	1199.063	355.434	106.19	10.14	199.80
F4	336.480	1199.125	355.994	106.25	30.96	250.04
F5	335.538	1199.106	355.445	122.14	10.14	200.04
F6	335.575	1199.046	355.741	121.92	40.16	250.05

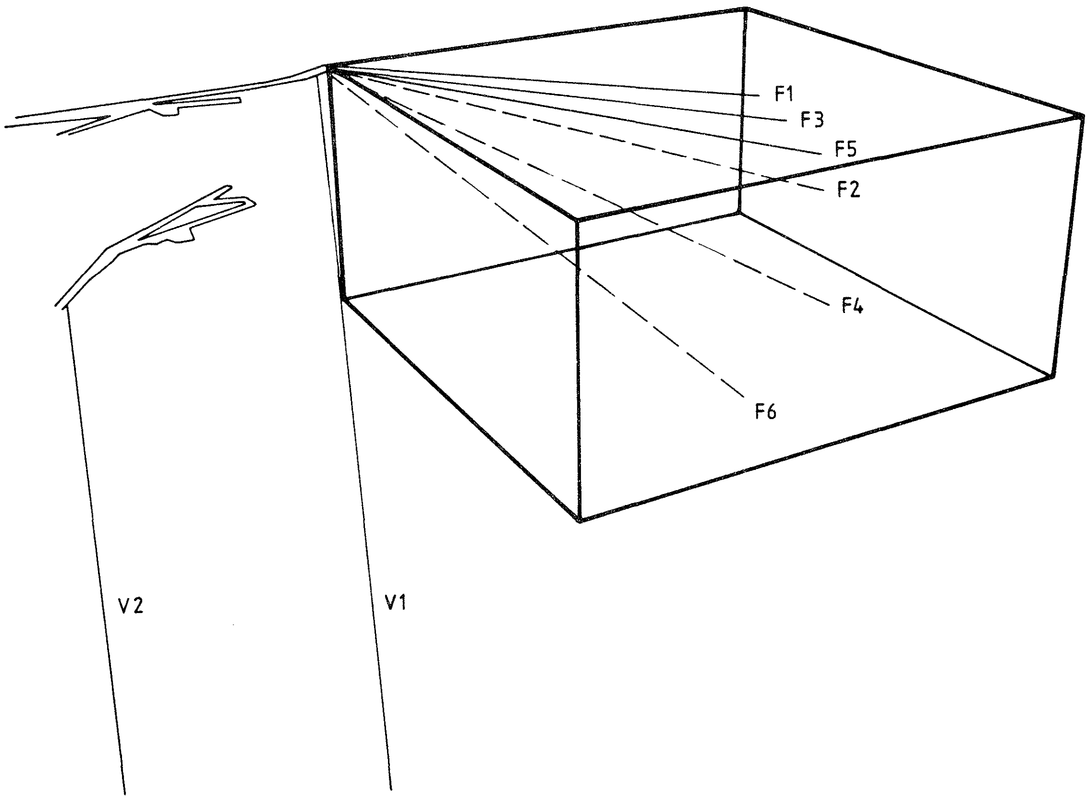


Figure 2.2 Perspective view of the boreholes at the Crosshole site.

2.2 GEOLOGICAL CHARACTERISTICS

The site has been characterized by a comprehensive program of singlehole geophysical and geological investigations. These investigations were performed in order to provide a frame of reference for comparison with the novel techniques developed as a part of the project. The singlehole investigations provided a description of the geological conditions at the site and the geometry of tectonized structures (Carlsten, Magnusson, and Olsson, 1985). This is summarized below.

The rock at the site consists of a fine to medium grained granite intersected by a few thin (less than 10 cm thick) pegmatites and quartz veins. The granite is fractured with the fracturing concentrated into zones of more intensive fracturing. The average frequency of fractures with mineral coating or altered surfaces taken over the total length of all six boreholes is 4.6 fractures/m. The undeformed granite between the zones is massive, fine to medium grained, and grey to pale red in color. The zones with more intensive fracturing generally show a number of signs of deformation such as brecciation, mylonitization, alteration, and red coloring. A concentration of fracturing combined with signs of deformation have been considered to indicate zones of significant lateral extent. In the evaluation of the singlehole data six zones or major units as they have been called were identified. The zones were identified by assigning letters to them. One minor zone was also identified close to the drift and this zone was assigned a numeral. This notation has been kept during the course of the project even if the orientation of some of the zones have changed due to the greater capabilities of the crosshole methods compared to the singlehole methods.

An underlying concept in the analysis of the singlehole data has been that zones with a significant lateral extent would be of greatest importance for the flow of groundwater. The granite at Stripa has a relatively high average fracture frequency. The fractures observed in the core represent the small scale features of the rock. The fractures observed have widths on the order of millimeters and they are observed over lengths of approximately the diameter of the borehole (in this case 75 mm). It is normally quite difficult to infer the lateral extent of features from this type of small scale information and other types of geological evidence and the singlehole geophysical logging data have been used as indicators of lateral extent.

Brecciation, mylonitization, alteration and red coloring have been seen as signs of faulting and hence as geological evidence of lateral extent. Features associated with faulting are also general evidence that there has been water flow in these features in geological time. The singlehole geophysical logging methods provide observations on a slightly larger scale than the fractures in the core. Roughly speaking, the singlehole geophysical methods can be said to provide data with a length scale of about one meter. In the analysis fracturing observed in the core combined with significant geophysical anomalies has been considered as an indication of lateral extent.

In short, the features have been defined as significant in the singlehole investigations where there was evidence of significant lateral extent. Increased fracturing, geological evidence of faulting and significant anomalies in the singlehole geophysical logs have been considered to constitute such evidence. An example of a singlehole data set is given in Figure 2.3 which shows a composite log of the singlehole data from borehole F2. The fracture zones (major units) identified are indicated in the figure. The zones are associated with significant anomalies in the resistivity and the sonic logs while responses in the neutron and density (gamma-gamma) logs are observed only at some of the zones.

The orientation of the identified zones has been deduced by combining data from all holes. The indications observed in the holes have been correlated under the assumption that the zones are roughly planar. Whether this assumption is correct is discussed in the Chapters to follow.

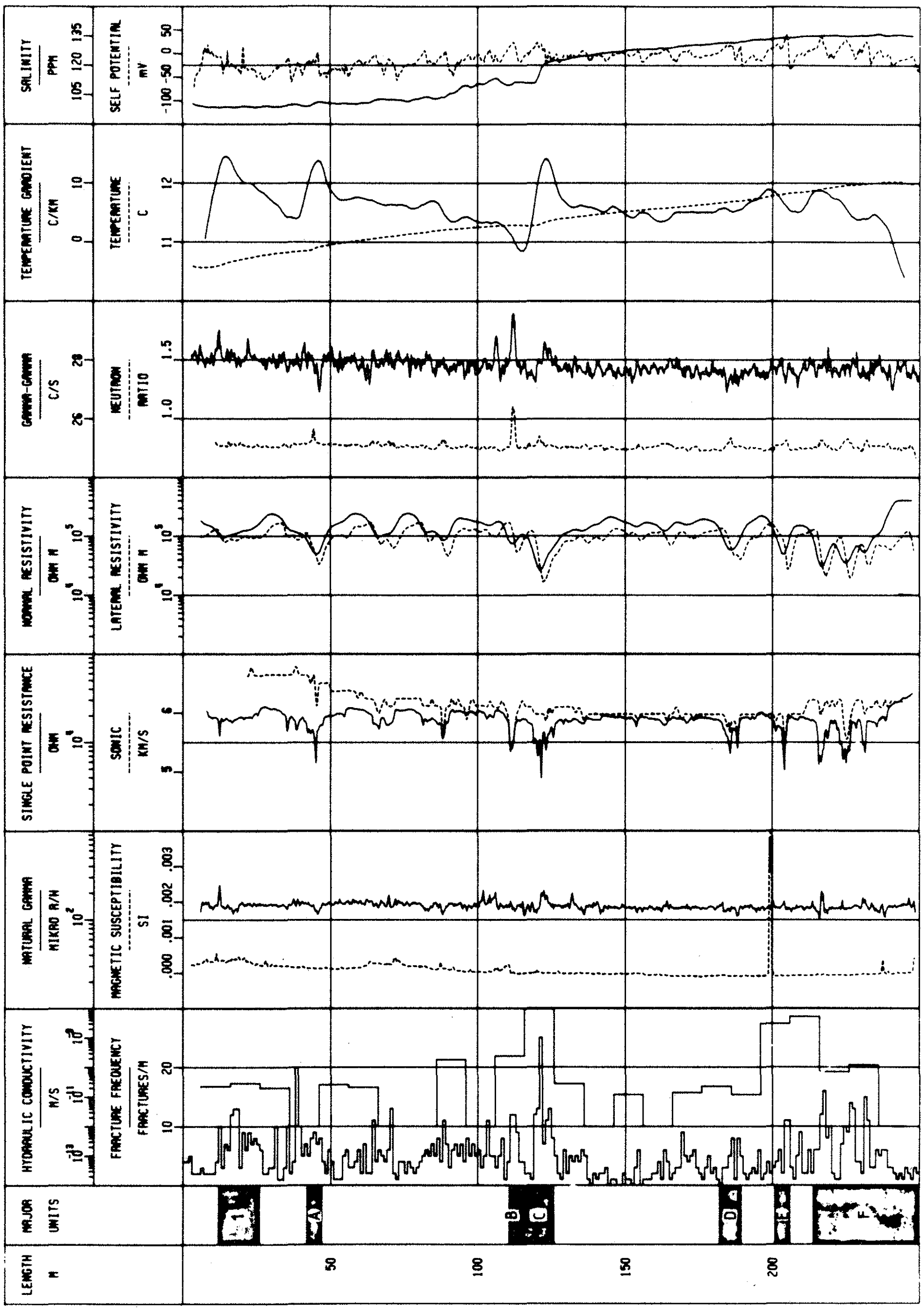


Figure 2.3 Composite log of results from singlehole geophysical, geological, and hydrological borehole measurements in borehole F2.

3 INVESTIGATION METHODS

3.1 BOREHOLE RADAR INVESTIGATIONS

3.1.1 Introduction

In the radar technique electromagnetic waves are used to obtain information about the structure of the rock. Short pulses of energy are transmitted into the rock and the scattering of the pulses from inhomogeneities give data on the location and electrical properties of the inhomogeneities. There is a frequency window from a few MHz to a few hundred MHz where wave propagation effects dominate and the attenuation of the radar waves is moderate. In the radar work performed within the Crosshole Program frequencies in the range 20 to 60 MHz have been employed. This corresponds to wavelengths from 6 m to 2 m in rock.

The radar investigations have comprised the design, construction, and testing of a new borehole radar system. The design of the new system started early 1983 and the first tests with the new system were performed in May 1984. The system can be considered to have been operational since September 1984. Since then a large number of singlehole and crosshole investigations have been performed at the Stripa Mine. Singlehole reflection measurements have been performed at Stripa in 16 boreholes with a total length of about 3 700 m, and in about half of them measurements have been made with two different frequencies. Six crosshole sections have been measured where each section contained approximately 1300 rays. The radar subprogramme has also comprised the development of interpretation schemes and software for the analysis of the obtained data.

3.1.2 The borehole radar system

At the start of the borehole radar project a thorough analysis was performed to define the basic features of a borehole radar system which would satisfy the objectives of the Crosshole Program, i.e. to detect fracture zones in granitic rock. This analysis resulted in a set of design objectives and a preliminary design for the new borehole radar system (Olsson and Sandberg, 1984). It proved possible to meet virtually all design criteria and it was even possible to obtain greater range than originally envisaged.

The radar system consists of four different parts:

- a microcomputer with two 5 inch floppy disc units for control of measurements, data storage, data presentation and signal analysis,

- a control unit for timing control, storage and stacking of single radar measurements,

- a borehole transmitter for generating short radar pulses,

- a borehole receiver for detection and digitization of radar pulses.

The radar system works in principle in the following manner: A short current pulse is fed to the transmitter antenna, which generates a radar pulse that propagates through the rock. The pulse is made as short as possible to obtain high resolution. The pulse is received by the same type of antenna, amplified, and registered as a function of time. The receiver may be located in the same borehole as the transmitter or in any other borehole. From the full wave record of the signal the distance (travel time) to a reflector, the strength of the reflection, and the attenuation and delay of the direct wave between transmitter and receiver may be deduced.

The recording of the signal is similar to that of a sampling oscilloscope, i.e. for each pulse from the transmitter only one sample of the received electric signal is taken at a specific time. When the next pulse is generated a new sample is taken which is displaced slightly in time. Thus, after a number of samples a replica of the entire signal is recorded as a function of time. The sampling frequency and the length and position of the sampled time interval can be set by the operator.

Optical fibers are used for transmission of triggering signals from the computer to the borehole probes and for transmission of data from the receiver to the control unit. The optical fibers have no electrical conductivity and thus will not support waves propagating along the borehole. Another advantage of optical fibers is that they cannot pick up electrical noise and as the signal is digitized down-hole there is no deterioration of the signal along the cable. The quality of the results are thus independent of cable length.

There is no direct connection between the transmitter and the receiver. Both probes are instead connected directly to the control unit and the transmitter and the receiver can be put into the same or separate boreholes. In other words, the radar may be used for both singlehole and crosshole measurements. The system also provides absolute timing of the transmitted pulses and a calibrated receiver gain which makes it possible to measure the travel time and the amplitude of the radar pulses in a crosshole measurement. This is to provide the data needed for a tomographic analysis.

Singlehole reflection measurements are normally carried out with a separation of measurement points of 0.5 m or 1 m. Each measurement takes about 20-40 s depending on the number of samples and stacks. This corresponds to about 100 m of measured borehole per hour in one meter steps.

The computer unit and the control unit are shown in Figure 3.1.1 and the borehole probes in Figure 3.1.2. The block diagram of the control unit, transmitter and receiver is shown in Figure 3.1.3 and the technical specifications of the system are given in Table 3.1.1.

An integral part of the radar system is the control software which includes the following facilities:

- selection of parameters controlling the measurement, e.g. signal position, sampling frequency, number of samples and number of stacks;

- control of measurement;

- display of radar results on color screen or matrix printer;

- signal processing including Fourier transformation, correlation, deconvolution and/or bandpass filtering;

- display of the signal or spectrum of single traces.

Table 3.1.1. Technical specifications of the borehole radar system.

General	
Frequency range	20-80 MHz
Total dynamic range	150 dB
Sampling time accuracy	1 ns
Maximum optical fiber length	1000 m
Maximum operating pressure	100 Bar
Outer diameter of transmitter/receiver	48 mm
Minimum borehole diameter	56 mm
Transmitter	
Peak power	500 W
Operating time	10 h
Length	4.8 m
Weight	16 kg
Receiver	
Bandwidth	10-200 MHz
A/D converter	16 bit
Least significant bit at antenna terminals	1 µV
Data transmission rate	1.2 Mb/s
Operating time	10 h
Length	5.4 m
Weight	18 kg
Control unit	
Microprocessor	RCA 1806
Clock frequency	5 MHz
Pulse repetition frequency	43.1 kHz
Sampling frequency	30-1000 MHz
No of samples	256-4096
No of stacks	1-32767
Time window	0-11 µs

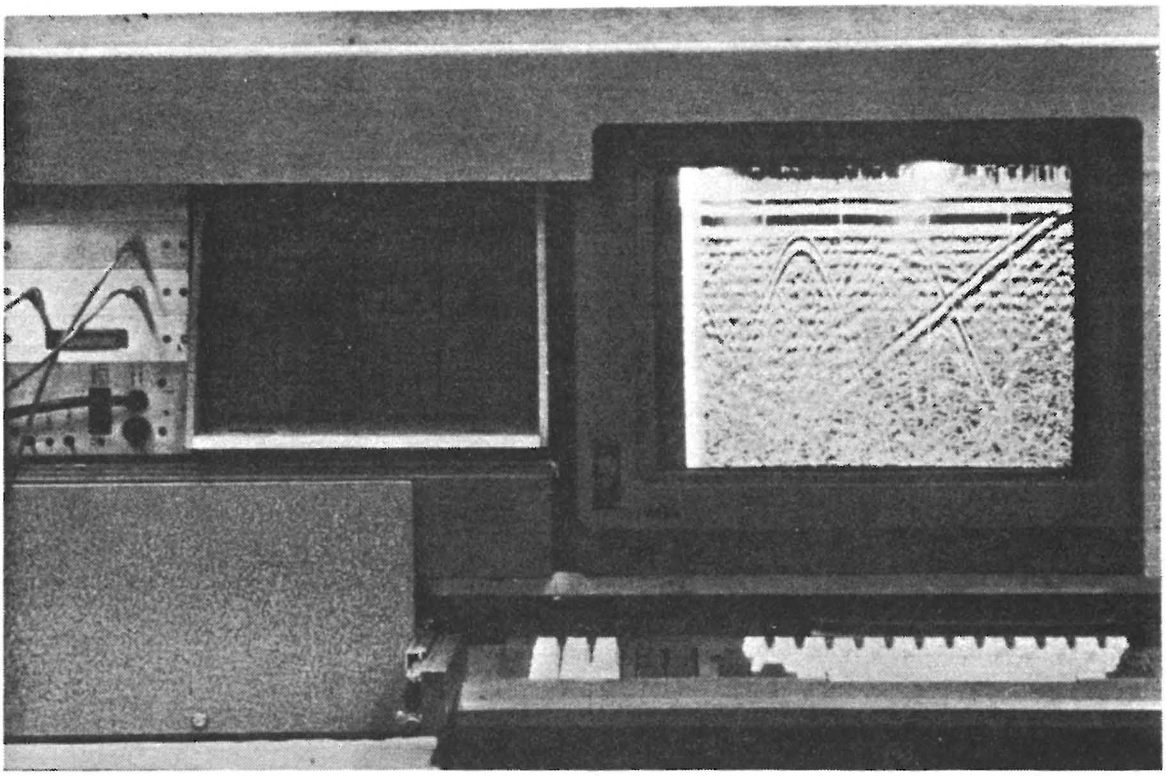


Figure 3.1.1 The borehole radar system units; computer unit and control unit.

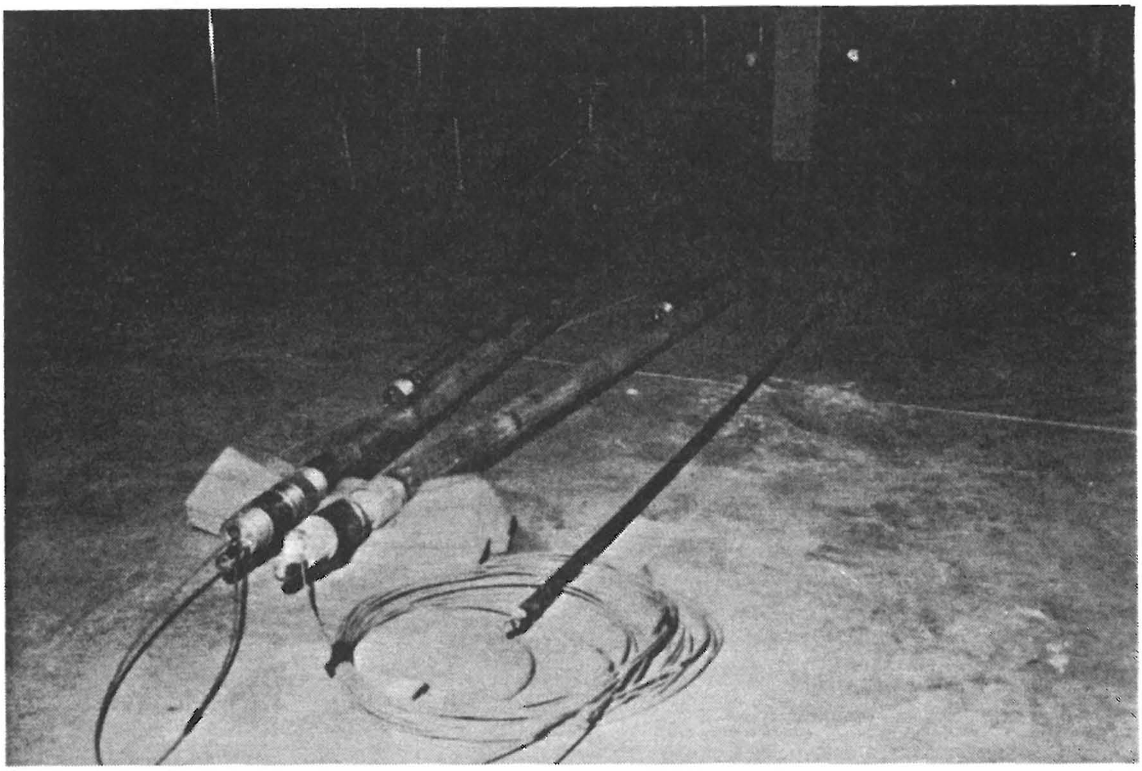


Figure 3.1.2 Borehole transmitter and receiver with batteries.

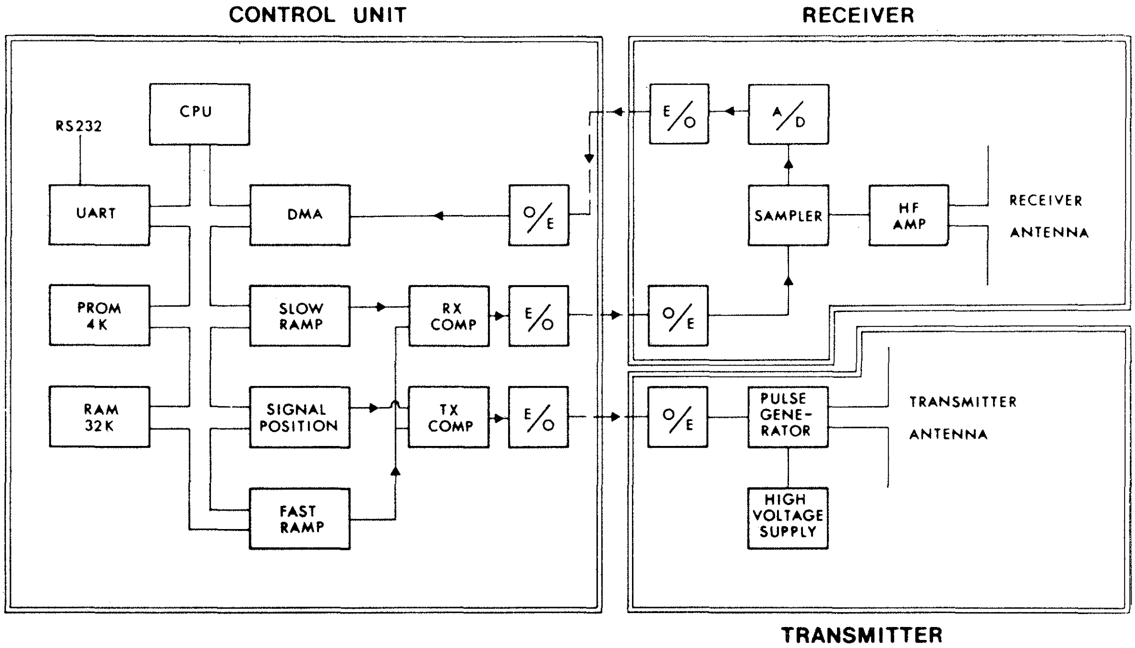


Figure 3.1.3 Block diagram of the borehole radar system.

3.1.3 Electric properties of granitic rock

Measurements of the electrical properties at radar frequencies show that the dielectric constant of granite has a value of about 5 and that it is essentially independent of frequency while the conductivity increases with frequency. The conductivity at radar frequencies is significantly higher than at zero frequency. Samples recovered from fracture zones show a slight increase in dielectric constant while the conductivity is about 30% higher than for unfractured rock. The difference in properties is correlated with the porosity of the samples. The data obtained on the electrical properties of core samples agree with the values obtained from in situ measurements. The velocity of radar pulses is 120 m/µs in the Stripa granite corresponding to a dielectric constant of about 6. The attenuation is about 28 dB/100 m at 22 MHz and 42 dB/100m at 60 MHz.

3.1.4 Singlehole measurements

The principle of a reflection measurement is depicted in Figure 3.1.4. The transmitter and receiver are lowered or pushed into the same hole while the distance between them is kept constant. The result is displayed in the form of a diagram where the position of the probes is shown along one axis and the propagation distance along the other axis. The amplitude of the received signal is shown in a grey scale where black corresponds to large positive signals, white to large negative signals and grey to small signals.

The distance to a reflecting object is determined by measuring the difference in arrival time between the direct and the reflected pulse. The basic assumption that the speed of propagation is the same everywhere in the rock mass has been verified during several crosshole measurements. As the radar is pushed step by step into the borehole the propagation time of the reflected pulse will vary in a characteristic manner typical of the reflector.

The basic task in the interpretation of singlehole reflection measurements is to identify the reflected pulses from individual objects and to obtain an accurate travel time estimate for each reflex. This task is often complicated by deterioration of the radar signal caused by various effects. For example the transmitted pulse is not the ideal spike which would be desirable. It has a certain time duration, which if excessive is called ringing, and which will limit the attainable resolution. The varying attenuation for different frequency components will cause broadening of the pulse with time. The radar signal is also to some extent contaminated by random noise (mainly from the receiver amplifier). Digital signal processing is applied to the radar data in order to enhance the reflections which give information about the structure of the rock.

Correlation filters have generally been found to be most useful in improving the radar images in that they are efficient in reducing noise. Bandpass and deconvolution filters have also been applied to some extent.

The two basic patterns obtained in a radar reflection map are point reflectors and plane reflectors as shown in Figure 3.1.4. The point reflector pattern agrees rather well with the strong hyperbola shaped reflection at a borehole depth of 175 m in Figure 3.1.5. This reflection is caused by a drift which extends in a direction perpendicular to the borehole so the reflection point is the part of the tunnel closest to the borehole. This measurement was made at a center frequency of 22 MHz corresponding to a wavelength of approximately 5.5 m in rock while the diameter of the drift is approximately 3 m.

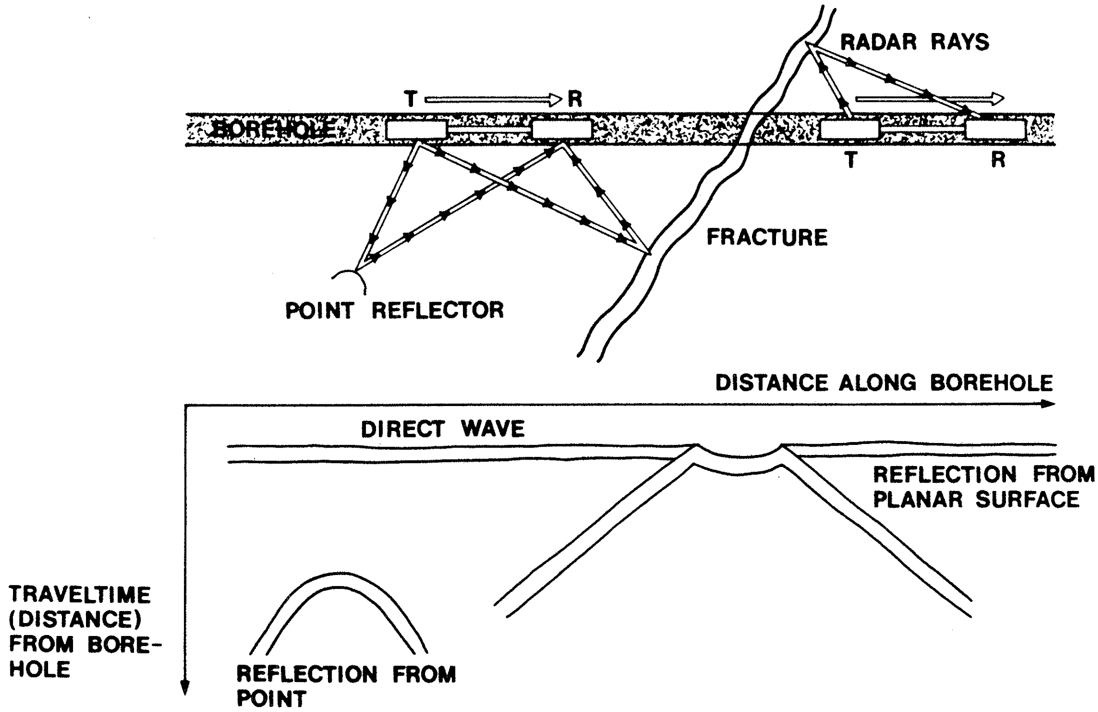


Figure 3.1.4 The principle of the borehole reflection radar and the characteristic patterns generated by plane and point reflectors.

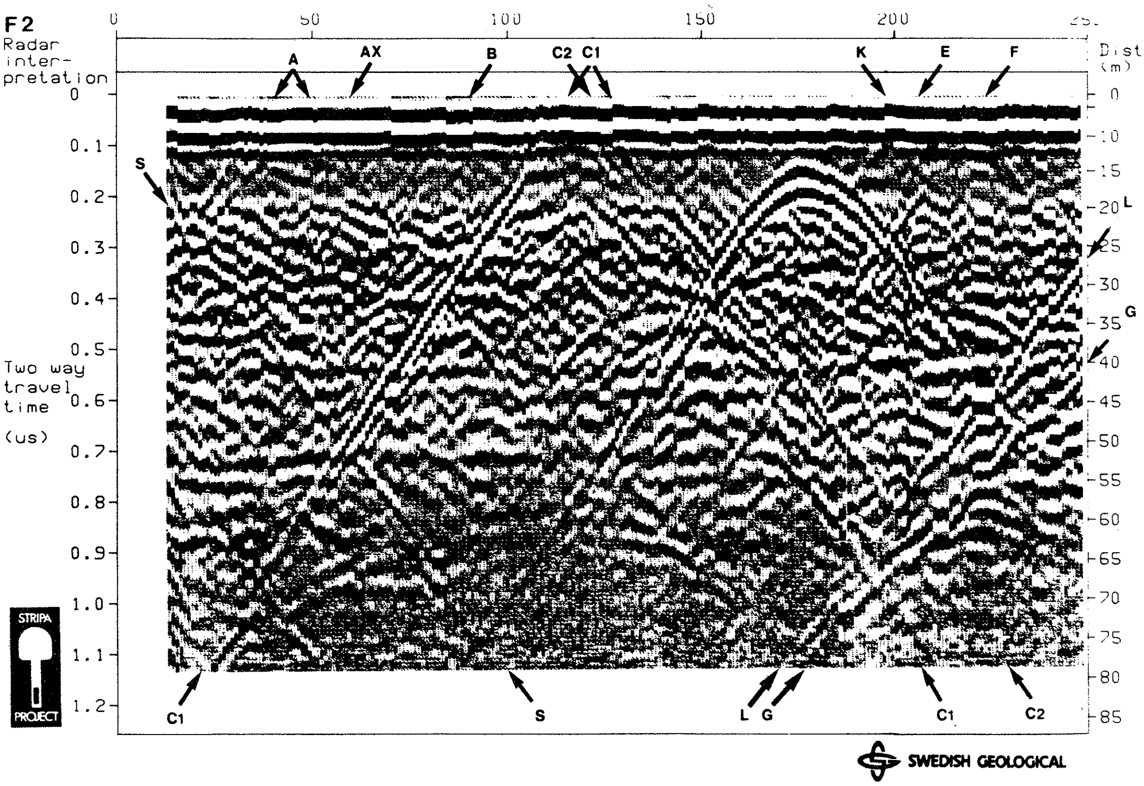


Figure 3.1.5 Radar refection map from the borehole F2 at the Cross-hole site in Stripa measured with a center frequency of 22 MHz.

One of the most important characteristics of the radar system is the available range. The identification of fracture zones is greatly simplified if the reflection pattern can be followed over large distances. One can then also observe that the reflectivity appears to vary over a fracture zone.

The typical radar map in Figure 3.1.5 shows that the radar system successfully solves the main object of the project, i.e. to detect fracture zones. Several zones are visible in this figure and the patterns agree with the theoretically predicted pattern for a plane reflector. The fracture zones must be quite plane since the patterns do not deflect noticeably from the predicted shape even when the zones can be followed over more than a hundred meters.

The fracture zones are characterized by the planar pattern. A plane reflector works like a mirror and is therefore the most efficient type of reflector and the only one likely to be observed at large range. As can be seen in Figure 3.1.5 some of the zones can be followed to a distance of 80 m from the hole. The range obtained is actually larger and in the measurement of the adjacent hole V1 a fracture zone was followed to a distance of 115 m. It is evident that the radar gives very detailed information about the extension of fracture zones at considerable distances from the boreholes. It is even possible to observe zones which do not intersect the borehole like zone L in Figure 3.1.5. That zone would intersect the borehole at about 270 m if the drilling had continued that far (the hole actually ends at 250 m).

The radar can be modified to peak at different frequencies by varying the antenna length and making the appropriate changes in matching. The resolution of pointlike objects and lines, such as the boreholes themselves, improves when the wavelength is reduced. However, when the frequency increases from 22 to 60 MHz (the frequencies used in most measurements in Stripa) the attenuation is almost doubled which means that the range is halved. A low frequency like 22 MHz, corresponding to an attenuation of about 28 dB/100 m, is therefore preferable when one is searching for fracture zones with large extension.

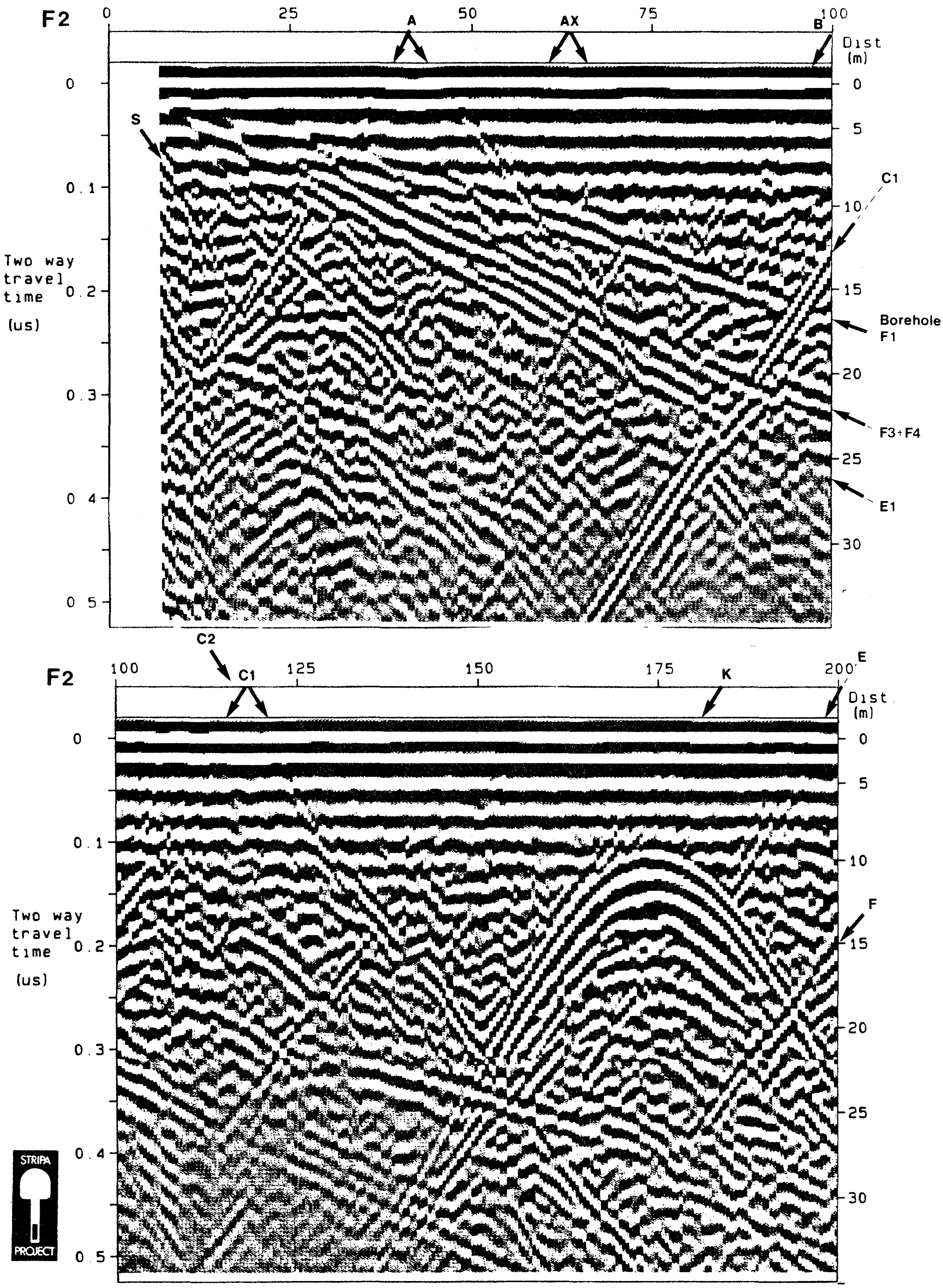


Figure 3.1.6 Radar reflection map from the borehole F2 measured with a center frequency of 60 MHz.

The decrease in range experienced when the frequency of the system is increased is seen in Figure 3.1.6 where the same measurement as in Figure 3.1.5 has been performed at 60 MHz center frequency. By comparing the extension of the fracture zones in Figures 3.1.5 and 3.1.6 it is easy to see that the range has been reduced to half the previous value. At the same time the resolution has been very much improved: fracture zones can be followed closer to the borehole and many more are visible than at lower frequencies.

The most dramatic change occurs for the boreholes themselves: at 22 MHz they can sometimes be faintly discerned in some radar maps while at 60 MHz they are clearly visible and very sharply defined. In Figure 3.1.6 several of them can be seen extending from the site at the origin of the diagram. The strong scattering is caused by water in the boreholes (diameter 76 mm): when the borehole is airfilled as at the beginning of borehole F6 the strength of the reflection is reduced. The position of the boreholes is well defined so the reflections provide an accurately known object suitable for calibration of the radar system. Such a calibration has been performed using all the 60 MHz measurements. It showed that the radar system works consistently and that the intersection angles can be determined quite accurately, down to one degree.

From the radar reflection measurements it is possible to determine the angle of intersection between the hole and a fracture plane and also the point of intersection. This is done with the aid of a theoretically computed nomogram.

Since the borehole geometry made it necessary to use dipole antennas, the radar images in Figure 3.1.4 and 3.1.5 are cylindrically symmetric. Consequently one can not obtain the complete orientation of a fracture plane from measurements in a single borehole. The orientation can however be determined by combining results from two or more boreholes.

When the radar system is used in the reflection mode the transmitter and receiver are moved along a borehole at a fixed distance, 2c, from each other. The radiation pattern of the antennas is axially symmetric about the borehole, so the origin of a reflection may be any point on a rotational ellipsoid with the focuses at the transmitter and receiver antennas respectively.

In the case of a planar reflector, such as a fracture zone intersecting the borehole, the two way travel distance, 2a, will vary according to the formula

$$2a = 2 \sqrt{(x^2 \sin\theta + c^2 \cos\theta)} \qquad (3.1.1)$$

where θ is the angle between the borehole and the fracture plane and x the distance along the borehole. Equation 3.1.1 is valid when both transmitter and receiver are at the same side of the fracture zone; otherwise there will be no reflection. Note that the reflection from a fracture plane is symmetric with respect to the intersection point between the plane and the borehole.

Using equation (3.1.1) it is possible to calculate nomograms corresponding to different intersection angles of a plane. A nomogram is produced by plotting the value of 2a for different positions, x, of the radar in the borehole for angles between 0 and 90 degrees. From a nomogram the intersection angles can be determined with varying precision: for fracture planes that intersect the borehole obliquely the angle can be determined with an accuracy of a few degrees while the error for almost orthogonal zones is tens of degrees. Nomograms provide a simple technique for evaluating radar data.

It is possible to analyze the orientation of a fracture zone in a consecutive manner when measurements from several adjacent holes are available, checking at all times that the measured data is in reasonable agreement with previous data. The analysis is performed with the help of a computer program which calculates the possible orientations of a fracture plane when its angle of intersection with a borehole has been determined from a radar measurement. The program can also calculate the possible orientations of a fracture plane when two points of intersection have been determined from the radar maps.

The orientation of a plane as determined by the direction of the normal is plotted in a plane using the Wulff projection, which is a type of stereographic projection (see Figure 3.1.7). Points where the curves intersect will be candidates for the correct orientation of the plane.

Considering the large number of angles and intersection points obtained for each zone from measurements in the six boreholes at the Crosshole site it may appear simple to obtain the correct position of a plane. This is however not generally the case: one reason is the uncertainty in the measured values and the fact that the boreholes subtend a limited angle, but it also appears as if the assumption that the fracture zones are flat does not hold over large distances. This is confirmed by the variations in measured radar angles and also by the undulating shape of the zones observed in tomographic analysis and radar measurements when a zone passes nearly parallel to the borehole.

A particularly clear example is offered by the so called Site Zone which passes directly through the Crosshole site. The reflection from this zone is easy to see in most radar plots. The width of the zone in the drift where it can be observed directly is 10-20 cm and this width is evidently sufficient to produce measurable reflections. When the normals corresponding to the measured radar angles are plotted in a Wulff diagram (Figure 3.1.8) a rather well defined intersection point is obtained in spite of the fact that the angles between the boreholes are small. Since we know in this case that only one zone is involved the scatter in the data points defines the accuracy that can at the very best be obtained when one is interpreting unknown zones. It is obvious that boreholes at large angles to each other are particularly helpful when an accurate result is required: see for example the curve defined by borehole F5. The curves actually seem to define two intersection points close to each other and it is at least possible that this is due to a real deviation of the zone from a plane since the points are defined by neighboring boreholes: E1, F1, F3 and F2, F4, F6.

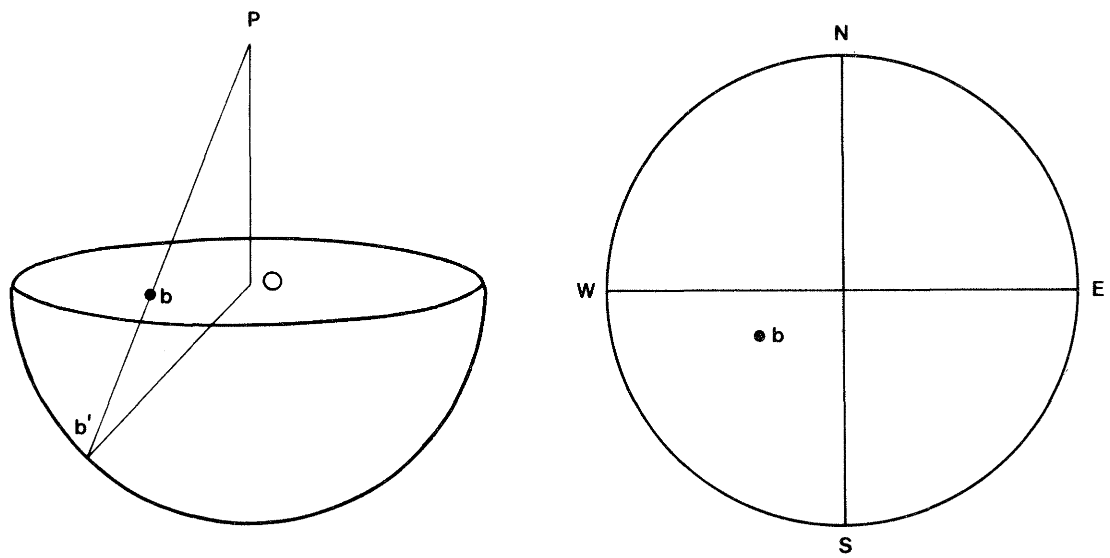
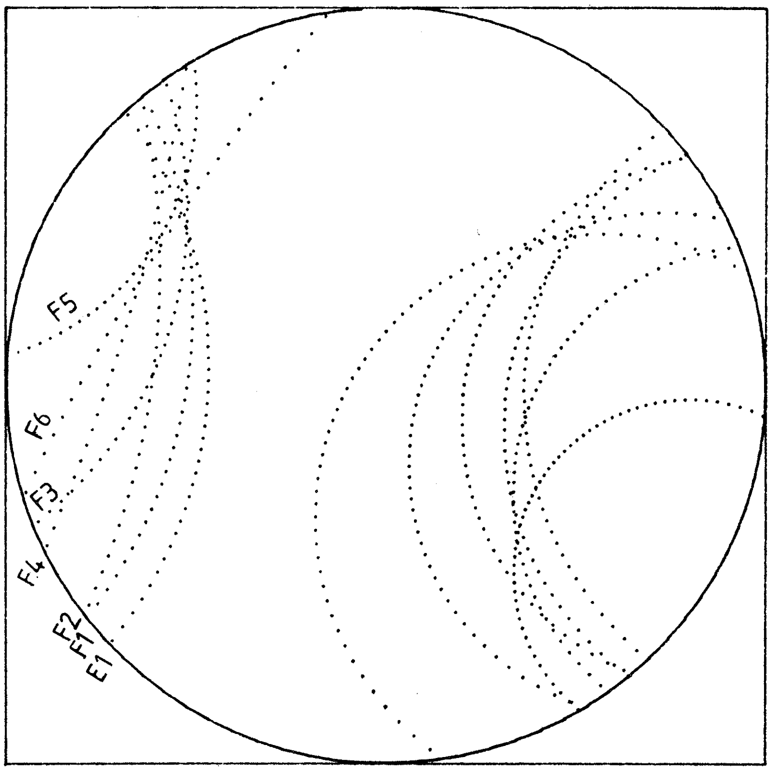


Figure 3.1.7 The principle of the Wulff projection.

NORTH



SOUTH

Figure 3.1.8 Wulff plot for the determination of the orientation of the fracture zone passing through the Crosshole site.

3.1.5 Crosshole measurements

In a crosshole measurement the transmitter and receiver are placed in separate boreholes. For each position of the probes a full wave record of the signal is recorded. The signal may be analyzed both with respect to the travel time and amplitude of the first arrival and with respect to the occurrence of later arrivals such as reflections. The objective of the crosshole radar measurements performed as a part of the Crosshole Program was to map the extension of fracture zones between boreholes through tomographic analysis. Hence, the measurement points were distributed to give optimal data for the tomographic analysis. The reflection data which was also obtained from the records can be considered more or less as a byproduct of the tomographic survey. If the objective had been to study reflections then the measurement points would have been distributed differently. It should also be noted that crosshole measurements provide a simple and efficient means for calibrating the radar system with respect to system losses as well as giving a radar velocity calibration for the single hole measurements.

Crosshole measurements have been made of the borehole sections listed in Table 3.1.2.

Table 3.1.2. Crosshole sections measured with borehole radar in the Stripa Mine.

Bore-hole 1	Measured section	Point sep.	Bore-hole 2	Measured section	Point sep.	Center freq.
F4	60-200 m	4 m	F1	50-190 m	4 m	22 MHz
F2	60-200 m	4 m	F5	60-200 m	4 m	22 MHz
F6	60-200 m	4 m	F1	60-200 m	4 m	22 MHz
F4	60-200 m	4 m	F5	50-190 m	4 m	22 MHz
F4	60-200 m	4 m	F5	50-190 m	4 m	60 MHz
F2	60-200 m	10 m	E1	60-200 m	2 m	22 MHz

The measurements were carried out in the following way: one of the probes was kept at a fixed position in the first borehole while the other probe was moved in the other hole where measurements were made with fixed increments, normally 4 m. Such a set of measurements has been termed a borehole scan. After each scan the probe in the first hole was moved to the next position and the measurement in the second hole was repeated. This was continued until each borehole section had been fully measured.

According to the reciprocity theorem the transmitter and receiver are interchangeable and it is irrelevant in which of the holes each probe is placed. Consequently it is also irrelevant which probe is fixed or which is moving during each borehole scan. In most of these measurements the receiver has been used as the fixed probe while the transmitter has been moved in the other borehole.

Tomography

Most of the crosshole sections measured at Stripa contain approximately 1300 rays. Such a survey requires roughly three working days.

A total of six crosshole sections have been measured at the Crosshole site and tomographic reconstruction have been made of both travel time and amplitude data. Some representative results of radar tomography are given in Chapter 4 in the presentation of the "Basic" and "Extended" models of the Crosshole Site. The complete set of results can be found in Olsson, Falk, Forslund, Lundmark, and Sandberg (1987). The tomographic results represent two different properties of the rock, i.e. the velocity and the attenuation of the radar waves. These properties have been measured in a set of planes between the boreholes listed in Table 3.1.2. Some of these planes intersect in space and a striking characteristic of the tomographic results is their consistency. The travel time and amplitude data generally show the same features at the same positions except for the drift which does not show up in the travel time tomograms. For the crosshole sections which intersect we see that the fracture zones identified in each individual tomogram also intersect at the correct position. The consistency of these results show that in spite of all the approximations made and the errors contained in the data the tomographic inversion gives results which are representative of the geological conditions in the rock.

The principles behind tomographic reconstruction and the methods used for analyzing the data are described in the section on "Geophysical analysis methods below".

Crosshole reflection analysis

When the transmitter and receiver are in different boreholes reflected pulses are observed after the directly propagated pulse has arrived. The direct pulse is the only part of the signal used in the tomographic analysis so the crosshole reflections provide additional independent information about the fracture zones.

Compared with single hole measurements previously invisible zones can be observed since the reflection geometry has changed considerably. Additional information about the orientation of the zones can also be expected. This was confirmed by the interpretation of data obtained at Stripa and in other measurements. It is particularly interesting that crosshole reflections in principle provide a complete determination of the orientation of a fracture zone. This is due to the additional freedom provided by a bistatic radar configuration. The disadvantage of the method is mainly that the analysis becomes more complicated and that the reflected signals may be weak since the reflected pulse will have a longer path to propagate than in single hole measurements.

Figure 3.1.9 shows a typical result from a borehole scan performed between boreholes F1 and F6 at the Crosshole site. During this measurement the transmitter was moved along F1 while the receiver was kept at a fixed position in F6. As the transmitter is moved the direct pulse registered by the receiver in F6 traces a hyperbola. After the direct pulse there arrive several pulses reflected from fracture zones. If the reflections are caused by fracture planes these curves are also hyperbolas. It is however difficult to use this geometrical information to extract information directly from the radar maps. A different method of analysis has therefore been used.

The bistatic radar configuration is defined in Figure 3.1.10. The receiver and transmitter are in known positions described by the vectors $\underline{\mathbf{x}}_0$ and $\underline{\mathbf{x}}_1$. The relation between the direct path between transmitter and receiver and the length propagated by a wavelet reflected in a plane is given by the expression

$$l'^2 = l^2 + 4(\underline{\mathbf{x}}_0\ \underline{\mathbf{n}})(\underline{\mathbf{x}}_1\ \underline{\mathbf{n}}) \qquad (3.1.2)$$

In principle all quantities in this formula except the vector $\underline{\mathbf{n}}$, which represents the normal of the plane, can be obtained from the measured data so from two or more measurements the two independent components of the unit vector $\underline{\mathbf{n}}$ can be determined.

The equation (3.1.2) indicates that one should plot the difference $l'^2 - l^2$, which is a linear function of borehole depth, x_1, for a plane reflector. Reflections are sometimes difficult to determine exactly in the radar pictures, since they are often weak and interference with stronger signals (especially the direct wave) can cause apparent deflections of the curve. It is consequently a useful test to plot the difference for each observed reflection and check that the lines are straight. After this control the slope and point of intersection with the abscissa are determined. The difficulty of identifying the reflections is often due to spatial aliasing which could be remedied by a smaller separation of measurement points in the borehole where the probe is moved.

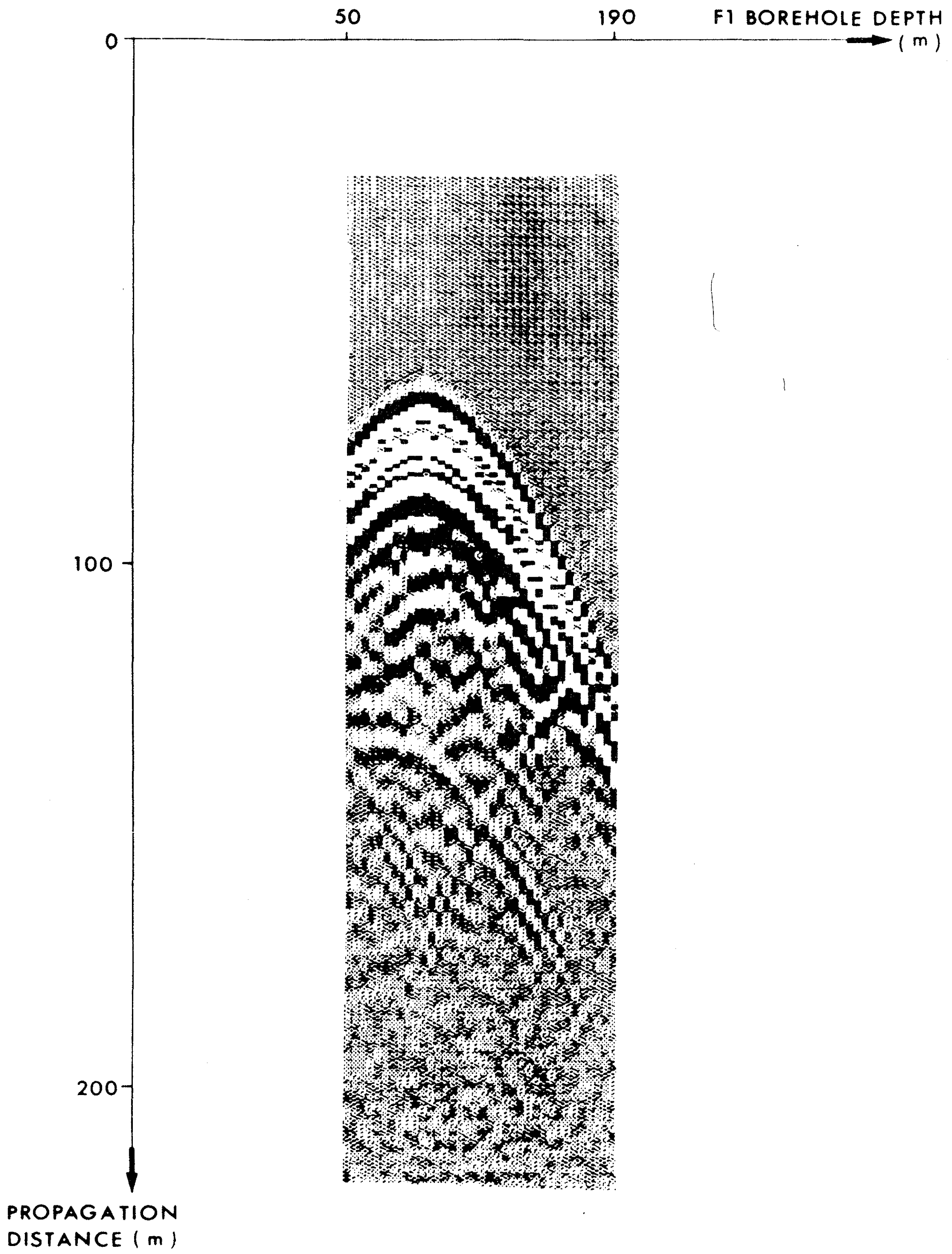


Figure 3.1.9 Radar map obtained with receiver fixed in F6 at 112 m while the transmitter was moved in F1. Center frequency 22 MHz.

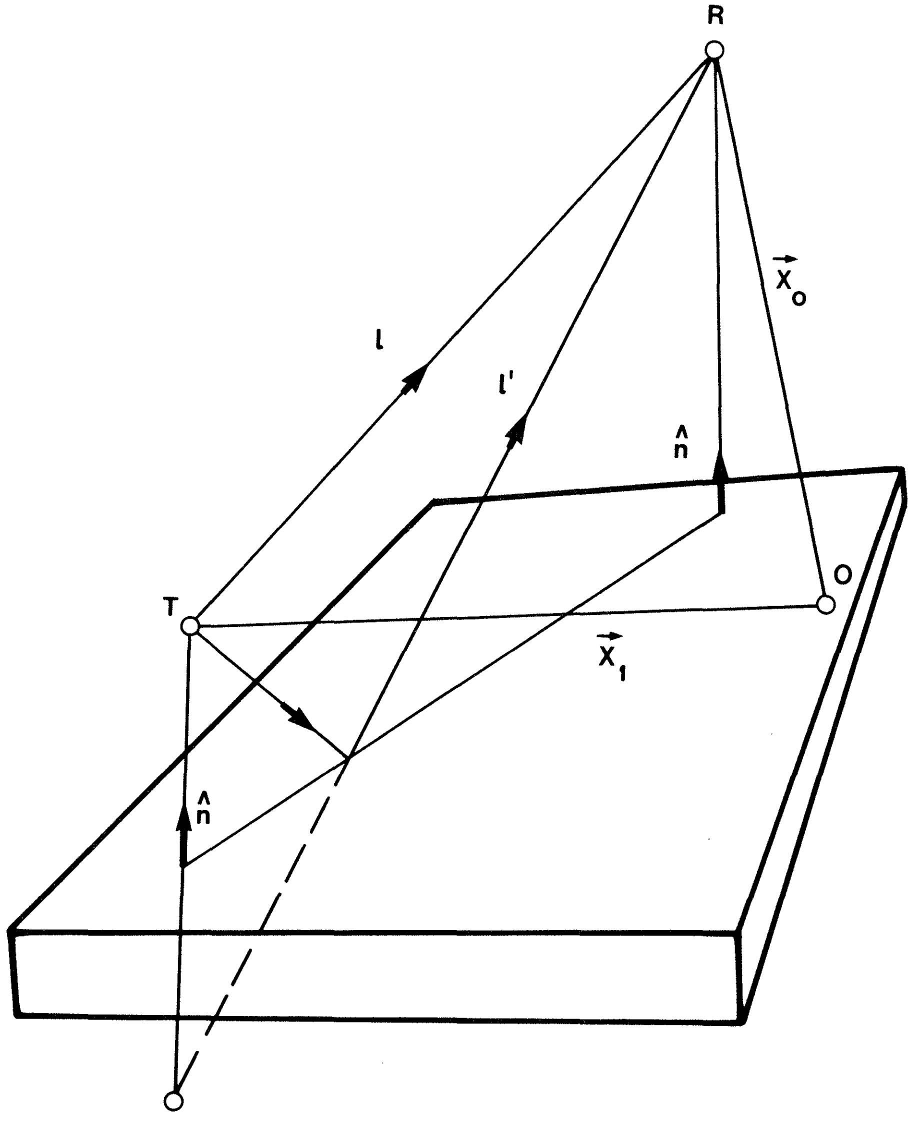


Figure 3.1.10 Principal ray paths in a bistatic radar configuration where the ray is reflected in a plane.

Figure 3.1.11 shows the data for zone E from measurements made with the receiver at three different locations in F6. The data points fall along three lines with different slope but they all intersect the abscissa at about 171 m in F1. The values for the slopes when introduced into equation (3.1.2) form a system of equations from which the orientation of the fracture plane can be obtained.

The analysis of the crosshole reflection data has shown that crosshole reflection measurements can be a powerful method of determining the position of fracture zones. It is sensitive to the quality of the data and the investigation has been of a preliminary nature since it is difficult to find enough strong and well defined reflections from each zone. A considerable improvement would be possible where experiments are specially planned to investigate crosshole reflections using image processing to simplify the identification of reflections.

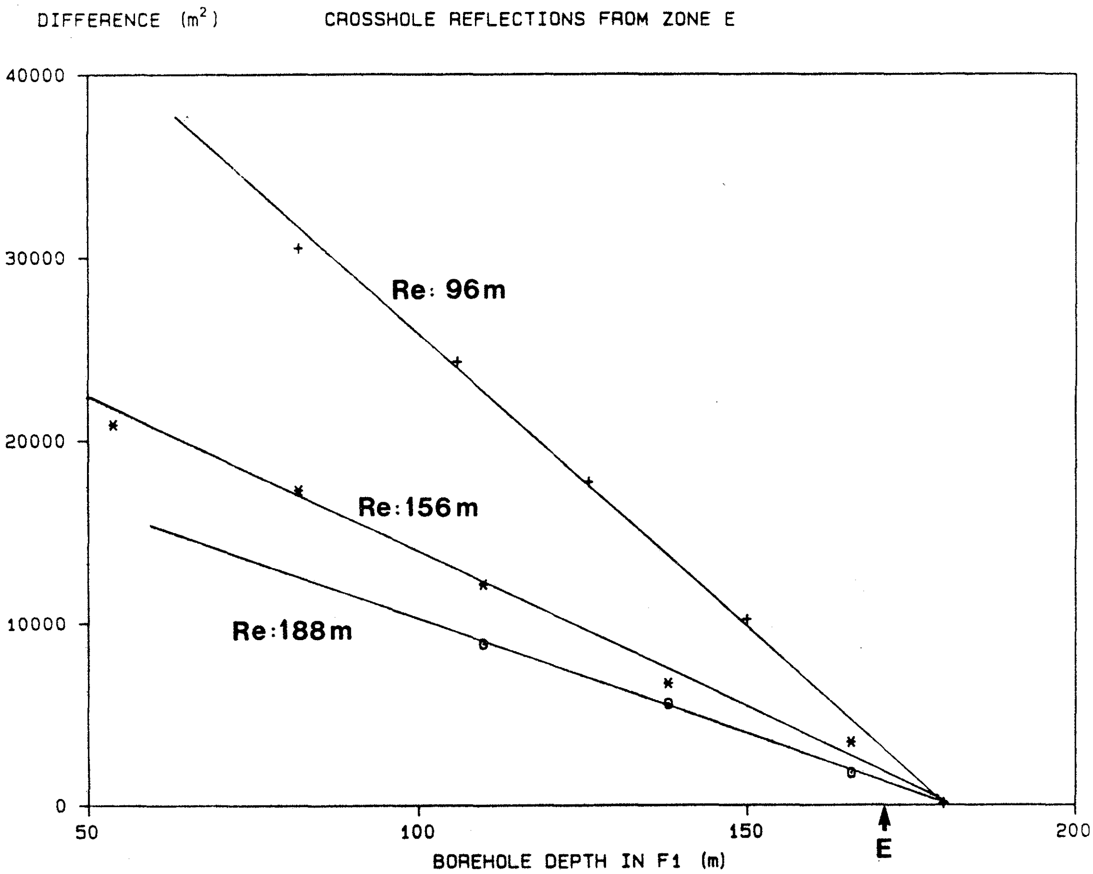


Figure 3.1.11 Plot of l'^2-l^2 for zone E in the crosshole reflection measurements between F1 and F6. Receiver fixed at 96, 156 and 188 m in F6. Center frequency 22 MHz.

3.2 BOREHOLE SEISMIC INVESTIGATIONS

3.2.1 Introduction

In the seismic technique elastic waves are used to obtain information about the structure of the rock. The elastic waves are of two kinds; longitudal 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 the Youngs 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 100 Hz to 5 kHz corresponding to wavelengths in the range 50 m to 1 m.

The seismic programme has included the following items

- Design and development of equipment for seismic borehole measurements (source, receivers and data collection system).
- Field tests at the Gideå site for large-scale measurements and at the Stripa Site for small and medium-scale measurements.
- Development of tomographic analysis and interpretation techniques.

3.2.2 Seismic measurement system

Crosshole seismic scanning is performed with a source in one borehole and detectors in another and, when possible, on the surface between the holes. Detailed coverage of the rock section between the holes is achieved by varying the position of the source and the receiver.

The frequency range needed for the crosshole measurements is markedly higher than for common exploration seismology due to the smaller survey scale and higher accuracy required. Thus, there are special demands on a system for crosshole measurements. Basically a seismic system for crosshole investigations consists of a seismic source, receiver unit, and a data collection system. The basic system components of one of the crosshole seismic systems used in the Stripa project is shown in Figure 3.2.1.

The purpose of the seismic source is to generate seismic signals of such energy and shape that they can be detected throughout the area under study.

Preferably a single-pulse source is used since it gives a signal which is easier to detect. It is preferable if the source generates both S-waves and P-waves since the former are more sensitive to the rock structure.

Two types of sources have been used within the Crosshole program; a borehole hammer and micro-explosions in the boreholes.

In the borehole hammer the seismic energy is generated by a hammer which is driven by a stiff spring against an anvil (Figure 3.2.2). The spring-based hammer mechanism is reset by a hydraulically activated ram. The transmission of energy to the rock is achieved by locking the device to the borehole wall. The unit is equipped with a hammer of 2.5 kg delivering 50 J per blow. The signal output is a transient starting with a high frequency onset (8-10 kHz) generated by the hammer striking the anvil. Lower frequencies (1-2 kHz) are generated by the oscillation of the instrument enclosure. Both P and S-waves are generated. The maximum S-wave energy is transmitted radially out from the borehole while the maximum P-wave energy is transmitted in the direction along the borehole.

Explosives are the most common means for generation of seismic waves. The main advantages are the high energy output (4 kJ per gram of explosive paste), the short pulse rise time and repeatability. In these experiments the charges have been small (1 to 100 gram) and the explosive paste has been centered in the hole to diminish the risk of borehole damage. The explosive sources produce mainly P-waves but S-waves are also generated.

A critical part of the seismic measurements is the determination of travel times. The time when the explosion occurs must be known with great accuracy. An accurate timing signal is obtained from two insulated wires which are welded together by the shock wave from the explosion. A special design of the circuitry permits the same pair of wires to be used for both triggering of the ignition device and transmission of the timing signal to the data collection unit.

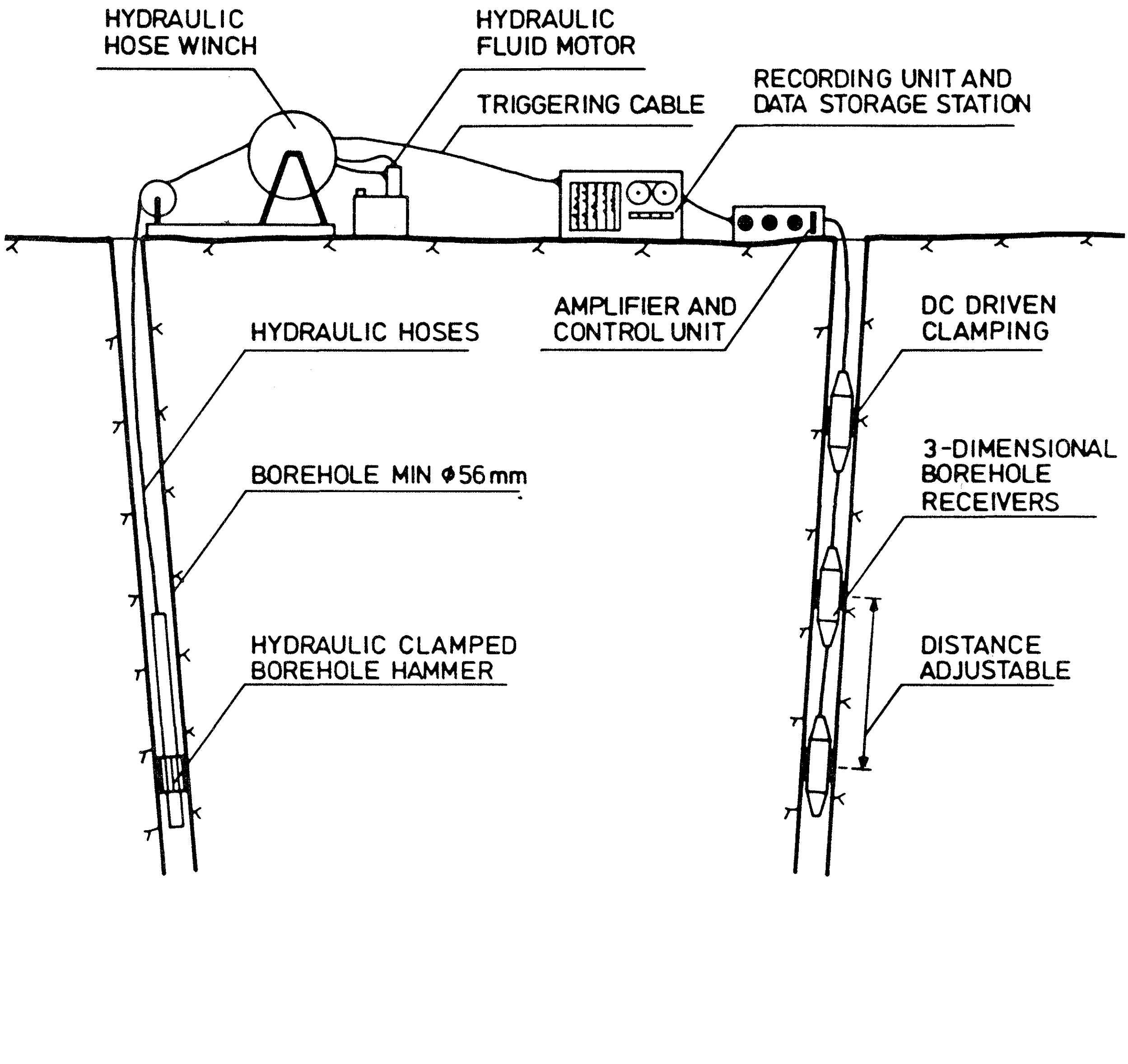


Figure 3.2.1 Main system components of a seismic borehole measurement system.

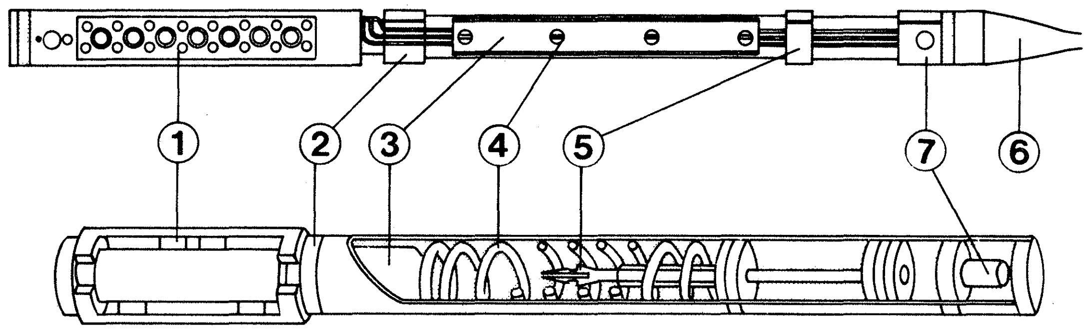


Figure 3.2.2 The borehole hammer source.

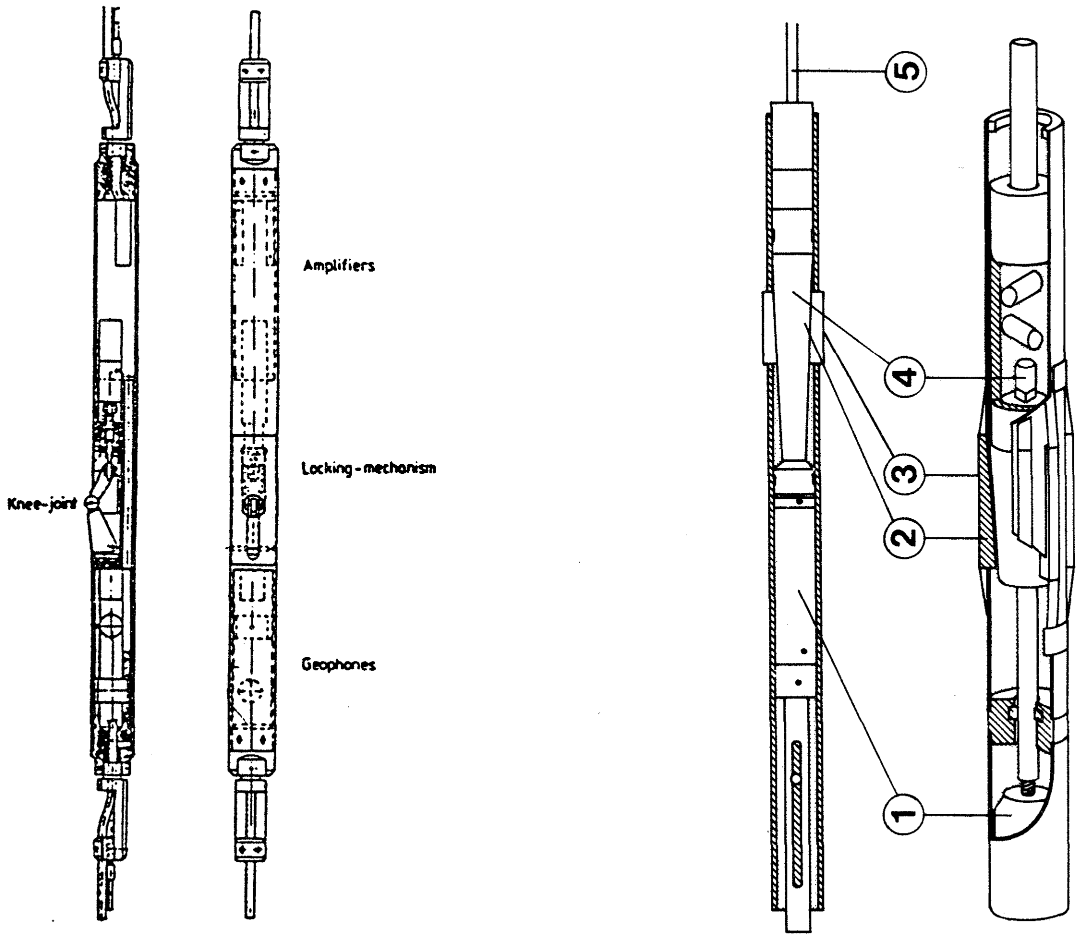


Figure 3.2.3 The two types of borehole receivers used within the project.

In seismic tomography measurements receivers can be placed both in boreholes and on the ground surface. For measurements on the ground commercially available geophones are suitable. A frequency response of up to 1 kHz is sufficient since the uppermost ground layers act as a low-pass filter, cutting away the higher frequencies in the seismic signal. When measurements are carried out in mines, where surface receivers can be fixed to the walls of the galleries, a higher frequency response is needed. Accelerometers with an upper frequency limit of 8 kHz are then used.

Two types of borehole receiving units have been used within the project (Figure 3.2.3). Both units have three accelerometers for measurements of the acceleration in three orthogonal directions. The diameter of the units are less than 48 mm and they can be used down to depths of at least 1 000 m. Both systems allow for the use of multiple receivers in the same borehole. The two types of receivers have different mechanism for locking the probes to the borehole wall. One unit uses a locking knee (Pihl, Hammarström, Ivansson, and, Moren, 1987) while the other one is locked by the symmetrically placed wedges (Cosma, 1987). Both systems ensure a good mechanical contact between the receiver and the borehole wall.

One of the data recording systems used for these experiments is based on a PDP 11/34 mini-computer expanded with various peripherals (Pihl, Hammarström, Ivansson, and, Moren, 1987). The analogue signals are sampled by a special microprocessor controlled subsystem called LPA (Maynard, 1978). It has two twelve bit A/D (analogue-to-digital) converters with a maximum sampling rate of 150 000 samples per second. The total number of analogue channels is 128.

The gains can be set from 0 to 48 dB in steps of 6 dB. The high-pass filter can be selected from 0 to 100 Hz. The low-pass filter, which also acts as an anti-aliasing filter, can be set from 100 Hz to 10 kHz. The filters have a slope of 24 dB per octave.

The software are of two types, real-time programs and data-analysis programs. The real-time programs deal with the actual sampling of the A/D converter, stores the data onto disc memory or magnetic tape and controls the settings of the filter and amplifier banks.

3.2.3 Crosshole tomography surveys

Crosshole tomographic surveys have been carried out both at the Crosshole site and at the Gideå site. The distances between the source and receiver points have for the Crosshole site been up to 150 m while separations of up to 1000 m were used at the Gideå site. Most crosshole surveys have been performed between two boreholes located in the same plane which makes a two dimensional analysis of the data possible. The seismic survey at the Gideå site also included a three dimensional distribution of source and receiver points and tomographic inversion of the data set.

At the Crosshole site six seismic sections have been measured. Five of these sections were measured with the mechanical hammer as a source. The source was kept in the borehole F4 while the receivers were deployed in the other five holes (F1, F2, F3, F5, and F6, Cosma, 1987). Most sections were measured with accelerometers but some measurements were made with geophone probes. The section F4-F2 was surveyed with geophone probes and the section F4-F6 was measured twice, both with geophones and accelerometers. The comparison of the results obtained from the different receiver probes showed that accelerometers are to be preferred for high resolution surveys of this type.

A test was also made where the signals obtained with borehole accelerometers and hydrophones were compared. The registrations were found to be quite similar. Hence it might be possible to replace the relatively expensive accelerometer arrays with a chain of hydrophones. This would make it possible to do the measurements in a shorter time, as more receiver units could be used, resulting in a larger number of rays for each transmitter position. If hydrophones are used no information will be obtained on the direction of the incoming wave.

The crosshole sections were measured with a separation of source and receiver points in the respective boreholes of 5 m. The ray pattern actually consisted of two sets which were made with a separation of measurement points of 10 m which were displaced 5 m relative to each other and superimposed. By this procedure a relatively dense and even ray pattern can be obtained with a reduced number of rays. The number of rays was about 250 for each section.

The borehole section F5-F6 was measured using micro-explosions as seismic sources (Pihl, Hammarström, Ivansson, and, Moren, 1987). Charges of 1 and 5 gram of explosive were used in the borehole F5. In this section nearly 500 seismograms were recorded.

Several checks on the data quality have been made to ensure that no systematic errors are present. This is particularly important when the contrasts are small, as is the case for the Stripa measurements. The deviations from the average velocity for all sections was very small, which indicates that the Stripa rock is relatively homogeneous.

The tomographic inversion of the crosshole sections were carried out assuming all source and the receiver points lie in the same plane. However, the boreholes curve slightly so the measurements points have to be projected into the plane best approximating the distribution of measurement points. The travel times were then corrected according to the alteration of distances. The remaining errors in source and receiver positions, which became more important with increasing depth, produced an effect similar to anisotropy which was also corrected for.

Measuring errors may occur when the arrival times are read off the seismic recordings. Tomographic inversion is very sensitive to such errors and a few erroneous measurements are sufficient to alter the general appearance of the resulting tomogram. Therefore noisy signals containing poorly defined arrivals were not used. A way of detecting data errors is to plot the residual error for each ray after running the tomographic program for a few iterations. Rays displaying large errors are then excluded.

After the corrections and error checking procedures have been applied fracture zones are readily identified in the tomograms. The tomograms give a detailed image of the fracture zones and it is possible to see how the thickness and velocity varies as the zones extend through space. Some of the seismic tomograms obtained from the data collected at the Crosshole site are shown in Chapter 4.

The other main effort in crosshole seismic testing was performed at the Gideå site which is located in the northern part of Sweden about 30 km north-east of Örnsköldsvik. The main purpose of these experiments was to apply the seismic crosshole method in a larger scale with distances between sources and receivers of up to 1000 m (Pihl, Hammarström, Ivansson, and, Moren, 1987). A triangular area, with a borehole in each corner, was selected. This made it possible also to carry out measurements in three dimensions. Futhermore, new source-receiver combinations (the so called VSP geometry with sources at the surface) were tested.

The Gideå site is dominated by sedimentary gneiss of varying degree of migmatization. The gneiss foliation structure has a generally small dip. This almost horizontal schistosity is also intensified by small horizontal joints in the rock mass. Most likely such a schistosity will cause velocity variations in different directions (Nilsson and Olsson, 1986).

The crosshole measurements were performed in a rock volume bounded by the three core-drilled holes 750 m to 1 km apart and 700 m deep. To achieve a improved coverage in crosshole scan and viewing angles, complementary seismic signals were generated in percussion drilled holes situated along profiles between the holes.

Two different source techniques were used, explosions in the borehole (traditional crosshole geometry), and explosions at the surface (VSP geometry). The crosshole configuration was also combined with geophone lines along the surface. The surface explosions intended for VSP surface-to-borehole measurement, were fired in 1.5 meter deep holes drilled along the lines between the three core-drilled holes.

The positions of the detectors in the boreholes were spaced with a separation of 10 - 50 m.

It was found that at recording distances up to 1000 m, a charge of 50 g usually provided a sufficient signal-to-noise ratio in this area. In all over 300 shots were fired in the entire experiment giving around 8,000 signal traces.

The analysis of the data from the Gideå site pointed at some problems which become important when tomographic measurements are performed in this scale. Ray-bending becomes significant mainly due to the increase of velocity with depth. Ray-bending can be accounted for by iterative ray tracing but the calculations will become much more time consuming. It was found that the main features seen on the tomographic reconstruction of the Gideå data (Figure 3.2.4) could be explained by the anisotropy of the rock. Anisotropy introduces more unknown parameters to the problem and the interpretation becomes less certain.

The three dimensional tomographic experiment showed that an inversion of three dimensional tomographic data is possible in principle. The ray coverage was not dense enough and consequently the resolution became very poor. It should be realized that it is exceedingly difficult and expensive to get a three dimensional ray coverage of such density that a tomographic analysis will be meaningful.

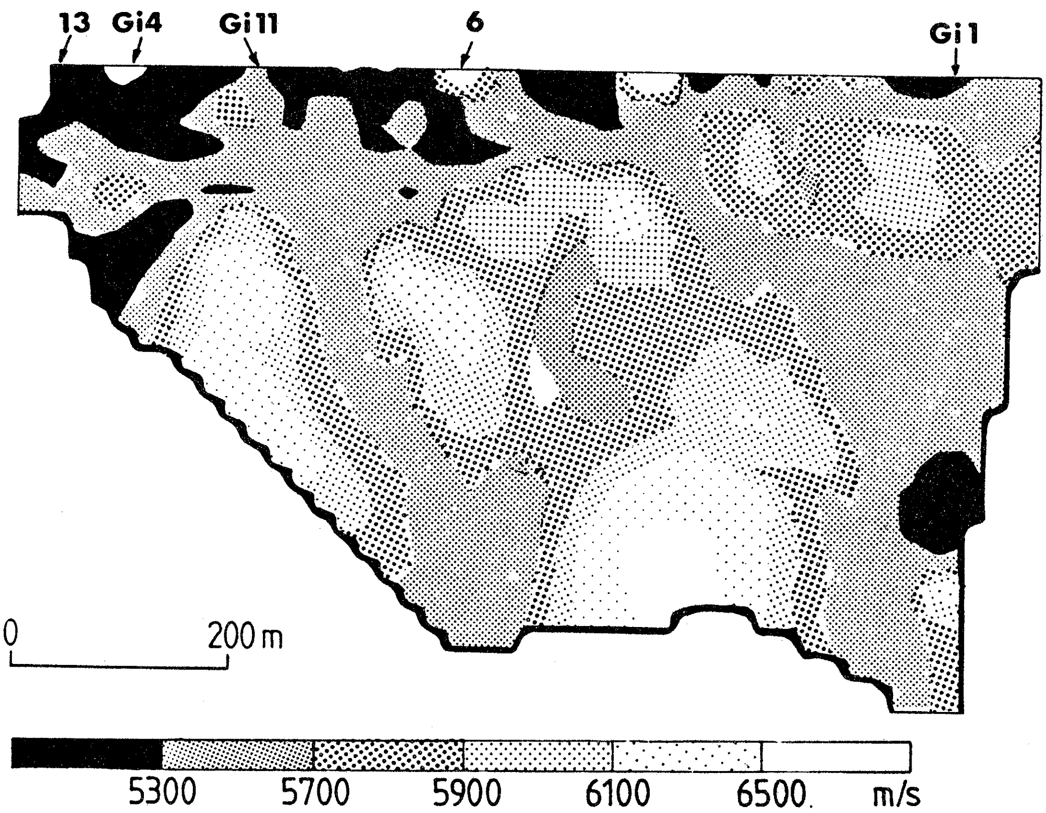


Figure 3.2.4 Tomographic map from one of the crosshole sections measured at the Gideå site.

3.2.4 Tube waves and reflection analysis

The seismograms recorded during the crosshole program showed indications of later onsets interpreted as reflections from the major features crossing the site and tube waves originating at the intersections of these features with the boreholes. Part of the transmission data available could also be used for reflection and tube wave analysis.

Tube waves are caused by the conversion of P-waves at positions in the borehole where there are changes in acoustical impedance. Such changes occur where fracture zones intersect the detector borehole.

Tubewave analysis has been performed on crosshole seismic data recorded in the boreholes F1, F2, F3, F5 and F6. An example of a recording where several tubewaves can be identified is given in Figure 3.2.5. Tubewave amplitudes were measured and compared with hydraulic testing results. Tubewave source depths were calculated and compared to hydraulically conductive zones and a reasonable agreement was found.

Because the test geometry for tomography processing differs from that required by reflection analysis only a part of the section between boreholes F4 and F6 were available for reflection analysis. The detector spacing in this part was approximately 2.5 m. Signals containing most of the reflection information were sorted out for further processing, which included items such as amplitude compensation, frequency filtering, deconvolution, move-out correction and coherency stacking.

In the analysis, a reflector was found at the position of zone "C", crossing the borehole F6 at 95 m and at 110 m. A weaker reflector at zone "A" was also found.

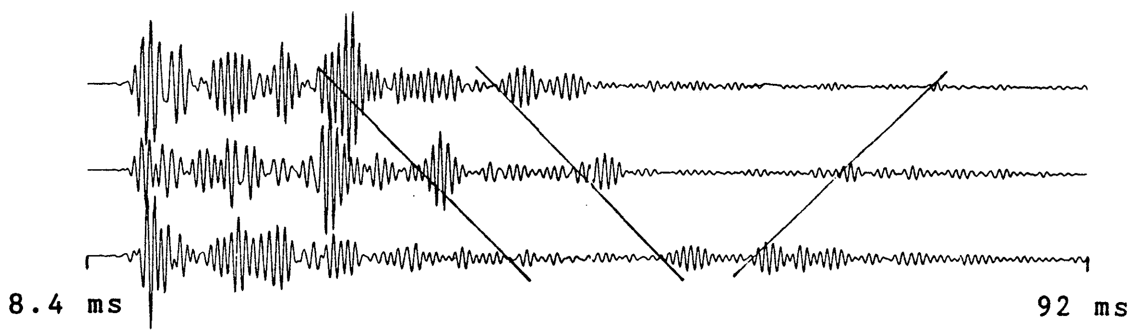


Figure 3.2.5 Seismic registrations showing the occurrence of tube waves. Tube wave onsets are connected by straight lines.

3.3 THE TOMOGRAPHIC ANALYSIS METHOD

The crosshole geophysics part of the Stripa II project was designed to allow an analysis of the data with the tomography method. This method provides information about the properties of the interior of a region from measurements at the boundary. In short the method amounts to probing the area with as many rays as possible. Each ray connecting transmitter and receiver can in principle be considered to give the average of a measured property of the rock along the ray (Figure 3.3.1).

In order to obtain an estimate of this property at a given point it is necessary that several rays pass close to the same point and that the rays have different directions and hence different information content. This puts severe constraints on the borehole geometry. The main restriction is that the source and receiver positions and hence the boreholes in practice must be confined to the same plane.

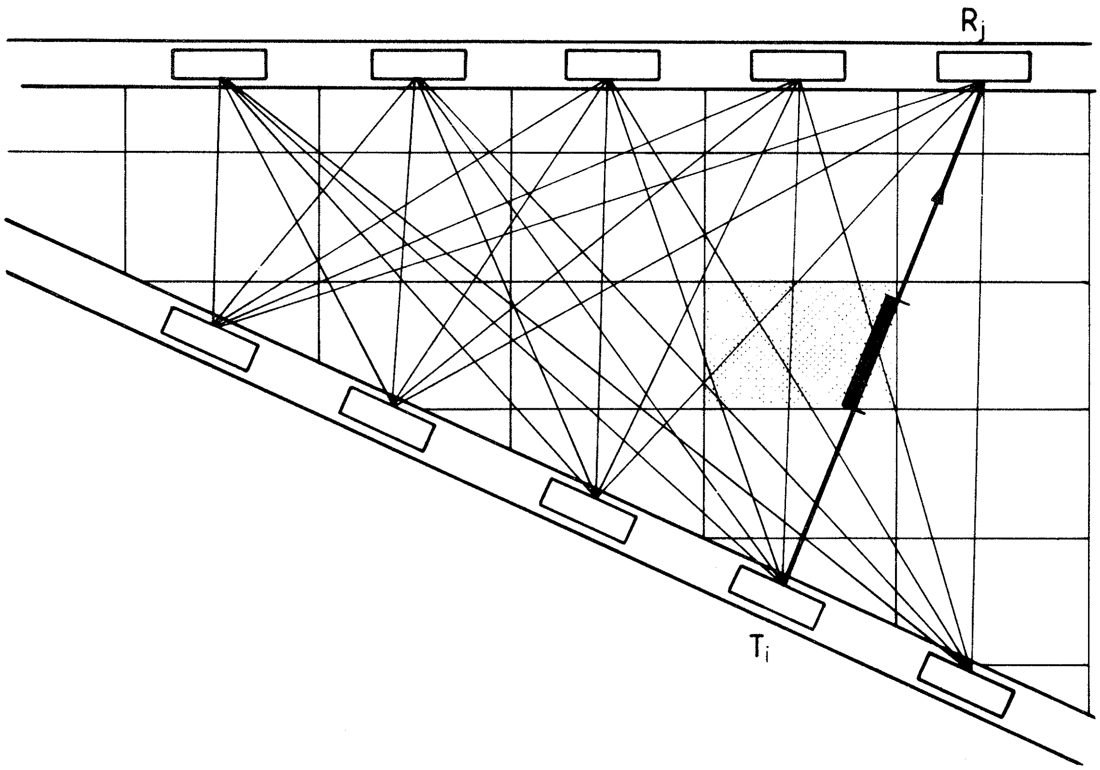


Figure 3.3.1 Generalized crosshole tomography geometry with a decomposition into cells and an example of a ray pattern. The contribution from each cell is considered in proportion to the length of the ray within each cell.

In mathematical terms the tomographic problem can be formulated in the following way

$$d_i = \int_{T_i(m)} m(x)\ ds \qquad (3.3.1)$$

where d_i is the measured data for ray number i. The objective of the tomographic inversion is to estimate the spatial distribution of some property, m(x), characteristic of the medium (x denotes the spatial coordinates). The data is thought of as being a sum (line integral) of this property along the ray path, $T_i(m)$, from the transmitter to the receiver. The actual ray path depends on the properties of the medium, m(x), and is normally the curve which gives the least possible travel time. The complex dependence of the ray paths, T_i, on the properties of the medium, m(x), makes the problem nonlinear. The problem can be linearized by replacing the curves T_i with straight line segments, L_i, connecting sources and receivers.

In a crosshole experiment data such travel time and amplitude of the direct wave between transmitter and receiver, i.e. the first arrival, can be extracted. It is assumed that the travel time can be constructed as a line integral of the slowness, s(x), along each ray, i.e.

$$d_i = \int_{L_i} (1/v(x))\ ds = \int_{L_i} s(x)\ ds \qquad (3.3.2)$$

The ray paths have here been assumed to be straight lines in order to make the equations linear and in this way simplify the inversion problem.

The expression for the amplitudes looks somewhat differently but if the logarithm is taken of the data the problem is linearized and can be solved by tomographic inversion. For a further discussion on amplitude tomography see Olsson, Falk, Forslund, Lundmark, and Sandberg (1987).

The mathematical problem of inverting the data to obtain the distribution of slowness or attenuation in the plane between the boreholes can be solved as follows:

First the equations are discretized. The plane between the boreholes is divided into a number of cells and the line integral is calculated as a sum where the contribution from each cell is considered in proportion to the length of the ray within each cell, cf. Figure 3.3.1. The slowness or attenuation of each cell may be described either as a single value for each cell or more generally as a sum of basis functions, f_j, such that

$$m(x) = \sum_{j=1}^{M} b_j \; f_j(x) \qquad (3.3.3)$$

The purpose of using basis functions instead of just a single value for each cell is that the basis functions can be made to represent some smoothing of the slowness values between adjacent cells. In some sense this also corresponds to an interpolation of slowness values between the midpoints of the cells. If the expansion into basis functions is inserted into (3.3.1) we obtain

$$d_i = \int_{T_i} m(x)\; ds = \sum_{j=1}^{M} b_j \int_{T_i} f_j(x)\; ds = \sum_{j=1}^{M} G_{ij}\; b_j \qquad (3.3.4)$$

where the matrix G is defined by

$$G_{ij} = \int_{T_i} f_j(x)\; ds \qquad (3.3.5)$$

Thus we have now a system of linear equations, where the number of equations corresponds to the number of rays, N, and the number of unknowns, b_i, to the number of cells, M. In matrix notation, we may write

$$\underline{\mathbf{d}} = \mathbf{G}\; \underline{\mathbf{b}} \qquad (3.3.6)$$

Depending on the ray pattern, this equation system can be both overdetermined and underdetermined at the same time. Also errors in the data may cause some equations to be in conflict. The most common method of solution for this type of equations is through minimization of some functional describing the difference between the experimental data and the data corresponding to an assumed model. An example is the functional $\underline{\mathbf{d}}\text{-}\mathbf{G}\;\underline{\mathbf{b}}^{\,2}$.

When solving the equation system there is a conflict between cell size and stability of the solution. In order to get the sharpest tomographic image one tries to use the smallest possible cell size. However this contradicts the requirement that many rays should pass through each cell, and may make the system unstable. A solution is then to introduce some form of damping. We have found that the best way is to assume that the slownesses (or velocities) of adjacent cells are nearly equal. Introducing equations constraining the solution in this way leads to the minimization of the functional

$$|\underline{\mathbf{d}} - \mathbf{G}\;\underline{\mathbf{b}}|^2 + \mu^2\; |\mathbf{C}\;\underline{\mathbf{b}}|^2 \qquad (3.3.7)$$

where the parameter μ is a measure of the damping and **C** is a matrix containing the equations for equal velocity in adjacent cells. μ, which has the dimension of length, determines the weight of the constraining equations. The practical consequence is that the differences in slowness between adjacent cells become smoothed to a certain extent, cf. the effects of a low-pass filter. This type of damping gives a smooth tomographic image without artifacts.

The solution to (3.3.6) has the following form

$$\underline{\mathbf{b}}=(\mathbf{G}^T\mathbf{G} + \mu^2 \mathbf{C}^T\mathbf{C})^{-1} \mathbf{G}^T \underline{\mathbf{d}} \qquad (3.3.6)$$

Here G and C are known and depend on the ray pattern and the division of the investigated area into cells. In other words, they contain the geometrical information about the experiment. The term within parenthesis is a square matrix which may be inverted through standard procedures and when this has been done a least squares estimate of **b** is obtained through matrix multiplication. However, the direct inversion of the matrix has practical limits since the matrix is large. The number of elements of G^TG is M^2, i.e. the number of cells squared, and this is usually a large number (in the order 10^6), which may prohibit the direct inversion of the matrix on ordinary computers.

For large matrices iterative procedures can be used to obtain the solution. Several different iterative algorithms have been tested within the framework of the Crosshole program. The conjugate gradients (CG) method is considered to be the most efficient one. The CG method uses second derivatives and converges quickly. It gives shorter computing times and better reconstructions of model examples than the other tested iterative methods. The inversion procedure is described in detail in Ivansson, 1983, 1984, 1985, and 1986.

3.4 HYDRAULIC INVESTIGATIONS

3.4.1 Introduction

The hydraulic investigations comprised two phases, a first phase of standard single borehole tests and a second phase of novel "sinusoidal" crosshole tests. An additional novel feature of the hydraulic investigations was the use of computer-controlled testing equipment designed to minimise errors and improve test control.

All hydraulic tests were carried out in zones isolated from the rest of the borehole using packers. The testing comprised the following parts:

type of testing	boreholes tested
single borehole (constant head injection)	F1 & F2
single borehole (pulse, slug and constant head: injection & abstraction)	F3, F4, F5 & F6
crosshole (constant rate injection and sinusoidal)	between boreholes E1, F1, F2, F3, F4 & F5

The division of the data-gathering into crosshole and single hole phases is not entirely exclusive since the crosshole tests required some extra single borehole tests. Hence some single borehole results were collected during the last phase of the hydraulic work. Another aspect of the testing operations was the need to stage the work so that the results of the geophysics were available before the crosshole testing. Hence the geophysics was carried out in short periods spread over the three years of the project. This is because the crosshole hydraulic testing is extremely time-consuming and therefore had to be targeted on potential zones of interest by the geophysics. Thus although the single borehole testing was carried-out comprehensively in all the boreholes the crosshole work was only done in specific zones. There was no crosshole work carried out in borehole F6 because the low water levels in that borehole precluded any abstraction using the pumps sited in the drift.

In all some 600 hydraulic tests were carried out. There were 90 crosshole tests which yielded about 30 positive results. A total of 472 zones were isolated during both types of testing though during the crosshole testing there were many zones which did not respond. In total this hydraulic work took about 55 weeks to carry out but this includes some lost time due to equipment failures.

3.4.2 Types of hydraulic test

Two types of test have been performed: single borehole and crosshole. Of these two types, there have been two forms of single borehole test (i.e. constant head/flow and slug/pulse) and two of crosshole (i.e. constant flow and sinusoidal). The constant head test consists of causing a sudden change of head in the test borehole and then maintaining this new head for a significant period (commonly about 2 hours). The rate of flow required to maintain this change of head is measured during this period. The constant flow test is very similar except that a constant flow is suddenly introduced into the borehole and the change of head is monitored. As time progresses the two tests become the same and the same analysis is applicable.

The slug/pulse test consists of causing a sudden head change in a section of borehole and then measuring the subsequent return of head to its original equilibrium value. In a slug test the head is changed and observed within a tube containing an open water level. In a pulse test, the head applied to an enclosed volume of water connected to the test zone is changed and observed. Hence the same mathematics underlie both slug and pulse tests with the only difference lying in the much smaller volume of water flowing during the pulse test.

The crosshole constant flow test is exactly the same as the single borehole version with the addition of measurements in borehole zones other than the source borehole. In the sinusoidal test a sinusoidally varying flow regime is applied in a packered-off source zone and measured in adjacent boreholes. In practice, it is easier to define a sinusoidally varying head in the source zone which is produced by a sinusoidally varying flow rate. Unlike the "constant" tests the pressure and flow versions of the "sinusoidal" test are interchangeable, separated by a fixed period of time. The application of these tests within the Crosshole Project is described below.

3.4.2.1 Constant head/flow tests

Almost all of the "constant type" tests were of the constant head variety. The constant head change was imposed by injecting water into the zone between two packers. The testing of F1 and F2 was carried out on a routine basis using the equipment and approach described in Carlsson and Olsson (1985) and consisted of a two hour period of injection at 100 m excess head over the apparent environmental head. (The environmental head of a zone is the equilibrium head that a zone will attain if isolated from the rest of the borehole for a long time.) In the testing carried out if F1 and F2 the excess head is imposed by using a gas overpressure system. In the constant head testing carried out in F6 the excess head varied between 10 m and 40 m and was imposed using the natural head difference between the zones of F6 and the instrument drift.

The single-borehole constant head test can be analyzed in three ways:

1. using the value of flow rate which was measured at the end of the period of injection in a "steady state" equation.

2. analyzing the change of flow rate with time during the period of injection: - a "transient method".

3. analyzing the change of head with time during the period of equilibration following pumping: - a "transient method".

All three methods were used during the Crosshole Programme. There are an equivalent set of analyses for constant flow tests (see Karasaki, 1986).

3.4.2.2 Pulse/slug tests

Pulse and slug tests were carried out using the computer-controlled equipment (see Section 3.4.3) constructed for the crosshole sinusoidal testing. The pulse tests were performed in two ways depending on the use of either the "receiver" borehole packer string or the "source" borehole packer string. In both cases the tested zone consisted of not only the volume of water between the packers but also the water contained within the tubing string between the zone and the drift where the "shut-in" valve (a valve which, when shut, isolates the test zone) was sited. Thus when the sudden head change is created in the test section the volume of all the pipework changes. The source string contained a variable length of 25 mm I.D. aluminum tubing whilst the receiver zones had a 300 m length of 3 mm I.D. to join the test zones to the shut-in valves.

The sudden head change required to start a pulse test was created by opening a valve in the instrument drift so that the pressurised water in the zone and pipework was allowed to drain into the instrument drift. Once the head in the test zone finished its initial sudden head decrease the valve was shut thus allowing subsequent equilibration. The amount of water involved in unit head change was measured by collecting this water in the instrument drift. The amount of water involved in pulse tests in these two configurations was in fact quite similar because the larger volume steel tubing was less elastic than the 3 mm plastic tubing. Connecting the test zone to atmospheric pressure in the drift resulted in a highly variable initial head disturbance. The head in the test zone was measured in the instrument drift in the case of the receiver string and within the test zone in the case of the source string. This siting of the measuring pressure transducer together with the use of small diameter tubing in the receiver string resulted in more reliable results from the source zone system.

For the slug tests, the tubing of the "reference pressure" system was utilised so that, after the initial head disturbance, the head recovered in the form of a water level moving within a 7.6 mm I.D. plastic tubing. The elasticity of the pipework was not taken into account since it amounted to less than 2% of the volume involved in the open water level fluctuation.

These two forms of test had effective ranges of applicability. Hence slug tests were most appropriate for transmissivities between 5 10^{-7} and 1 10^{-9} m^2/s whilst pulse tests were best when transmissivity was less than 1 10^{-8} m^2/s. When transmissivity exceeded 1 10^{-7} m^2/s a constant head test was used.

The analysis of slug tests is a "transient" method which yields a value of hydraulic conductivity and a rough estimate of specific storage. The same mathematics underlies slug tests as pulse tests so the interpretation method is the same. The concept of "effective radius" is used to provide direct equivalence between the two. The amount of water which flows into (or out of) the packered-off section of a borehole for a unit change in head determines the duration and radius of influence of both slug tests and pulse tests. For a slug test this is obviously proportional to the radius of the tubing in which an open water level fluctuates (r_c of Cooper et. al., 1967) plus the compliance of the system. The compliance of the system is usually negligible compared to r_c. For a pulse test, the amount of water involved in flowing into or out of the test zone can be equated to water movement within a fine incompressible tube whose radius is r_e. For a 10 m long straddle in a borehole of 76 mm diameter and without system compliance the value of r_e will be about 0.3 mm (assuming that the shut-in valve is at the end of the test zone and the packers and tubing are rigid). In practice, system compliance alone was equivalent to an effective radius of about 0.3 mm so that values for the total system with the minimum of downhole tubing amounted to about 0.45 mm.

3.4.2.3 Crosshole constant flow tests

Very few crosshole constant flow tests (usually termed aquifer or interference tests) were carried out. They had exactly the same form as the single borehole version of the test except that the head was monitored in adjacent boreholes as well as the source borehole. When it was carried out within this programme it was done using the computer-controlled equipment. In contrast to the sinusoidal testing, it was generally carried out using long lengths of borehole as source and observation zone. The main drawback of these tests was the fluctuating heads common in the mine environment which form the background against which the hydraulic signal has to be perceived.

The technique has been widely developed in the fields of aquifer testing and oilfield reservoir testing so that there is a wide literature concerning the interpretation of this type of test. Almost all interpretations are based on the transient approach yielding values of K and S_s.

3.4.2.4 Sinusoidal tests

The sinusoidal pressure test is a crosshole technique in which a small zone of one borehole is subjected to a sinusoidal variation of pressure whilst similar zones in adjacent boreholes are monitored (Figure 3.4.1a). The pressure variation in the source zone is created by a carefully controlled regime of injection and abstraction. The receiver zones should detect sinusoidally varying pressure which has a smaller amplitude than that in the source zone. Also the observed signal should lag behind the source zone signal since the pressure waves take some time to diffuse from the source to the receiver (Figure 3.4.1b). The decrease in amplitude and the retardation of the received signal depend on the geometry and hydrogeological properties of the flow paths in the vicinity of the source zone.

This approach has several advantages and disadvantages when compared to the usual constant-flow aquifer test, namely:

<u>Advantages:</u>

1. The oscillating signal (of known frequency) is detectable against a changing background pressure (especially important in mines).

2. The testing is essentially point to point enabling complex flow geometry to be built up from simpler smaller elements.

3. There is no net discharge so equilibration times are small enabling rapid movements of the source zone position.

4. The frequency of the test is specific and can be changed to investigate different components of the bulk rock hydrogeology, i.e. fracture properties and matrix properties.

<u>Disadvantages:</u>

1. The distance of penetration of measurable pressure fluctuations is less than in the constant-flow method.

2. The test requires equipment which is more complicated than straightforward abstraction testing.

The test was first proposed by Black and Kipp, (1981) for a limited range of flow geometries. It differs from normal interference testing in that the results of a particular test can be summarised entirely in terms of the amplitudes and the phase lag.

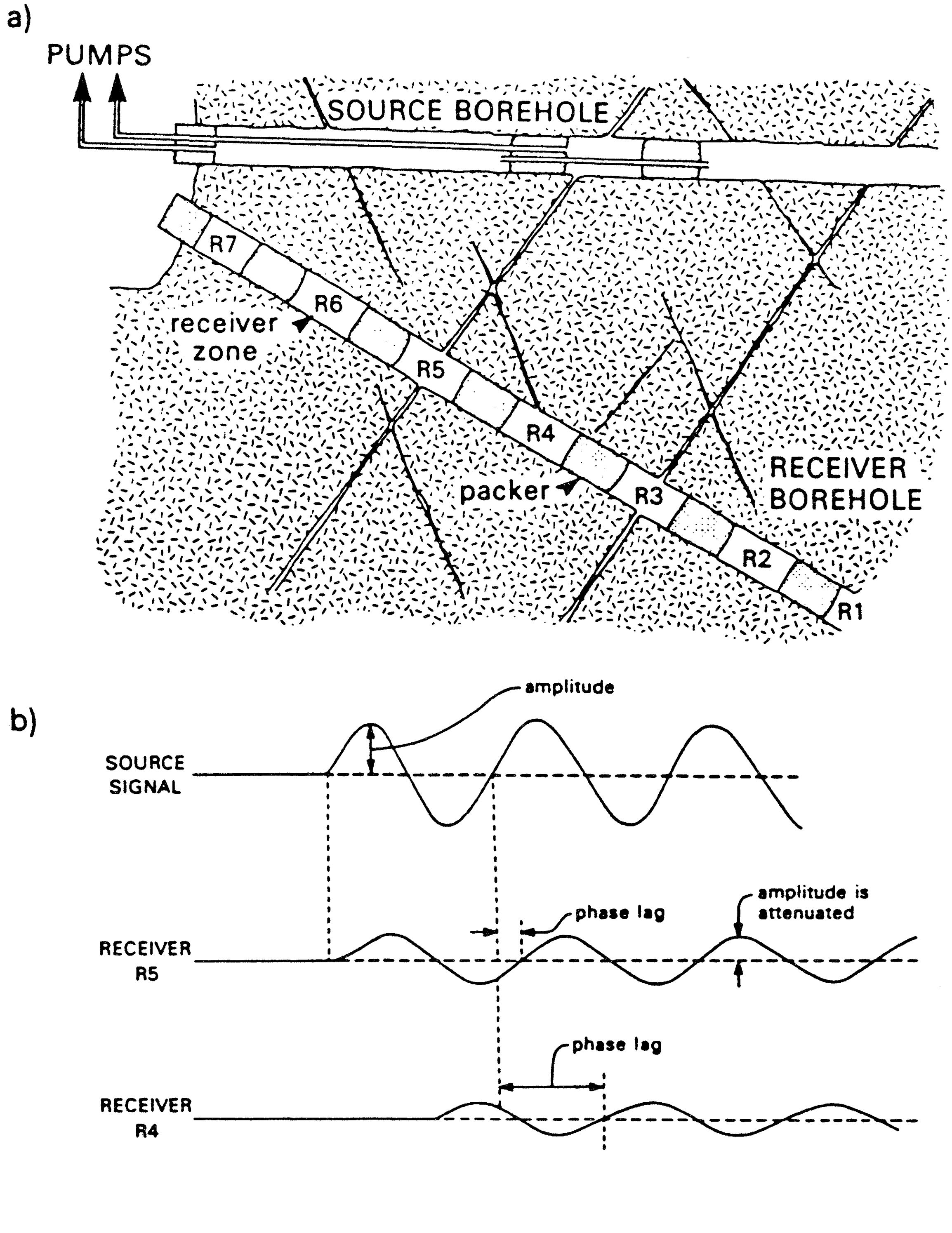


Figure 3.4.1 Schematic representation of a) source and receiver borehole arrangement b) attenuation and phase lag.

3.4.3 Hydraulic testing equipment

3.4.3.1 Need for computer-controlled equipment

The decision to use sinusoidal tests as the main method of crosshole testing resulted in the need for a set of testing equipment which could create sinusoidal variations of head in a source zone. Previously this had been done manually (Black and others, 1982) but this was obviously unsatisfactory in a programme of frequent tests. The requirements of sinusoidal testing, such as the need to both abstract as well as inject, formed the basis of the specifications for the system. It had also been discovered in previous testing that the location of the source zone signal required precise definition and should not be allowed to "spread" to the rest of the source borehole. This defined another of the characteristics of the system, the control of the head in the rest of the source zone borehole. Based on previous experience, certain other system characteristics were incorporated into the equipment. These included such aspects as the ability to measure pressure within the source zone, the ability to check for and measure pressure transducer drift and the ability to seal at their mouths the boreholes containing packer strings. The computer-controlled hydraulic testing system is described in detail by Holmes and Sehlstedt (1987). A brief summary is included below. The system is unusual compared to all previous hydraulic testing equipment because the tests are actually controlled by the computer based on criteria supplied by the test operator. All previous equipment only used computers for data acquisition.

3.4.3.2 Equipment description

The equipment is made up of six basic modules:

1. source borehole
2. source borehole control board
3. receiver borehole
4. receiver borehole control board
5. pumps
6. central micro-computer

During testing the packer assemblies for the source and receiver boreholes are located in two of the six boreholes. The various pumps, valves and inflation equipment are positioned in the instrument drift from which the boreholes extend out into the rock. The source borehole (Figure 3.4.1a) contains two hydraulically inflated packers which can be separated by a variable length of pipework to produce a test zone between 1 and 20 metres long. A rod string is used to position these and connects the source zone (between the packers) to the pumps which inject or abstract water to create any required variation in pressure (termed the hydraulic signal). The source zone pressure is monitored by a 35 Bar transducer located downhole immediately adjacent to the test section. A by-pass tube through the packer assembly connects the two lengths of borehole either side of the packers, jointly termed the rest-of-borehole zone. A transducer (35 Bar) measures the pressure of this zone.

All the rods, tubes and cables pass through a tapered sealing manifold. This device is bolted onto a flanged pipe which is grouted into the end of each of the boreholes within the array. Rubber elements are compressed by a pressure plate and seal around the pipes and tubes passing through the manifold. They can operate to a maximum pressure of 40 Bars and stop the source borehole from loosing pressure by water draining into the drift. All the boreholes are sealed by plates during testing and their pressures monitored by 35 Bar transducers.

Two pumps are operated in the mine working area. One injects or abstracts water from the source zone, under computer command, to generate hydraulic signals. The other responds to pressure changes in the rest-of-borehole zone caused by water flowing around the isolating packers. Any pressure fluctuations are damped out to ensure that the hydraulic signal originates from the source zone and is not derived from leakage of the signal to the rest-of-borehole zone. Both pumps are identically constructed. Each comprises a finely machined cylinder with a tightly fitting double-acting ram. This water pump is moved by a direct coupled, hydraulically-augmented mechanical driving ram, the exact linear position of which, is controlled by a stepping motor. Solenoid valves are fitted to the entrance and exit ports of the water cylinder to control the direction of flow. Each pump has an "on board" microprocessor, acting as an interface, which accepts commands from the central microcomputer to increase or decrease the flow rate. These are interpreted to vary the stepping rate and solenoid status to provide the required rate and direction of flow.

The receiver borehole (Figure 3.4.1) contains six hydraulically inflated packers which isolate five short and two long zones. All the tubes emerge from the borehole through a tapered sealing manifold, similar to the one on the source borehole, and continue to a "pressure measuring board". The board comprises a group of solenoid-actuated valves and pressure transducers. The tube from each zone is isolated from the "pressure measuring board" by a solenoid-actuated "access valve". The pressure in the tube is measured by opening the appropriate "access valve" and hence connecting the tube directly to an absolute pressure transducer with a range up to 35 Bar. For more detailed measurement two differential transducers (1 and 7 Bar), which measure zone pressure relative to a variable reference pressure, are located in the system. The reference pressure is contained in a "reference pressure tube" which is actually a long plastic tube installed in a nearby mine shaft. The height of the free upper surface of the column of water in this tube can be varied to match the pressure in the receiver zones. This pressure is measured by another 35 Bar transducer.The differential transducers allow zone pressures to be measured to a greater accuracy than is possible using absolute transducers. The pressures are measured by opening valves in turn so that the zones are accessed successively to the differential transducers. A disadvantage of this system is the time required to complete a scan which may approach several minutes. However, this is offset by the accuracies attained and the lack of transducer drift owing to the use of one transducer and the reference pressure.

The key element in testing is the ability of the control system to generate the hydraulic signal in the source zone. The central computer calculates a predicted curve of given shape (sinusoidal, square, constant rate etc.) based on information (amplitude, frequency etc.) provided by the operator. In the control cycle the computer compares the measured source zone pressure to the predicted and commands the pumps to increase or decrease the injection or abstraction rate to follow the curve. During testing, this cycle is repeated, on average, every ten seconds. The rest-of-borehole pressure is controlled in a similar manner.

3.4.3.3 Data handling for analysis

The tests were recorded by the central control computer under a system of file headers which identified the type of test together with the position(s) in the borehole where the packers had been situated. The computer down the mine was not big enough to carry out any analysis so the files were transmitted via the telephone system to a microcomputer on the surface. There was then a system of programs installed on this micro-computer to analyze the basic data. These programs produced either derived results or derived data depending on the type of test involved. Hence pulse and slug tests were analyzed to yield derived values of K and S_s whereas sinusoidal tests were processed to yield values of amplitude attenuation and phase lag (see "SINEFIT" in Black et.al., 1986).

3.4.4 Results

The different types of result from the hydraulic tests that were carried out have natural scales associated with them. It is proposed that the measurements carried out within the Crosshole Project had the following natural scales:

K from single borehole tests	- small scale
K, S_s and geometry from crosshole tests	- intermediate scale
head distribution from single borehole tests	- large scale

The results are presented (as far as possible) in order of increasing scale.

3.4.4.1 Single borehole tests

The six boreholes of the Crosshole Site, taken together, represent 1282 m of testing all within a rock volume of about 3 million cubic metres. They should therefore, being in close proximity, give very similar results.

Table 3.4.1 Hydraulic conductivities of the boreholes.

borehole	hydraulic conductivity (m/sec) average	mean
F1	$1.6\ 10^{-10}$	$4.8\ 10^{-11}$
F2	$2.6\ 10^{-9}$	$1.9\ 10^{-11}$
F3	$7.2\ 10^{-9}$	$2.6\ 10^{-10}$
F4	$2.2\ 10^{-9}$	$5.2\ 10^{-11}$
F5	$2.0\ 10^{-9}$	$1.7\ 10^{-10}$
F6	$1.5\ 10^{-8}$	$2.2\ 10^{-10}$
(all boreholes)	($5.0\ 10^{-9}$)	($8.6\ 10^{-11}$)

As can be seen in Table 3.4.1 the boreholes are comparatively similar in their average properties. Borehole F1 in the north of the site is the least conductive of the 6 boreholes whilst F6 (in the south) is the most conductive. The average and mean hydraulic conductivity differs by between one and two orders of magnitude. The boreholes where the difference is around two orders of magnitude (i.e. F2 and F6) are those boreholes which contain a single packered-off interval which is much more conductive than the rest of the borehole. F1 is a low conductivity borehole, contains no identifiable permeable zones and hence has mean and average conductivity differing by only half an order of magnitude. The other boreholes are intermediate between these extremes. The frequency distribution of the combined results (Figure 3.4.2) shows the distinct cut-off at a hydraulic conductivity value of 1 10^{-12} m/s. The distribution is slightly skewed towards lower values but this may be due to the lower conductivity results being overestimates. This is quite possible in the constant head testing as a result of the limited time available but is less likely in the pulse testing.

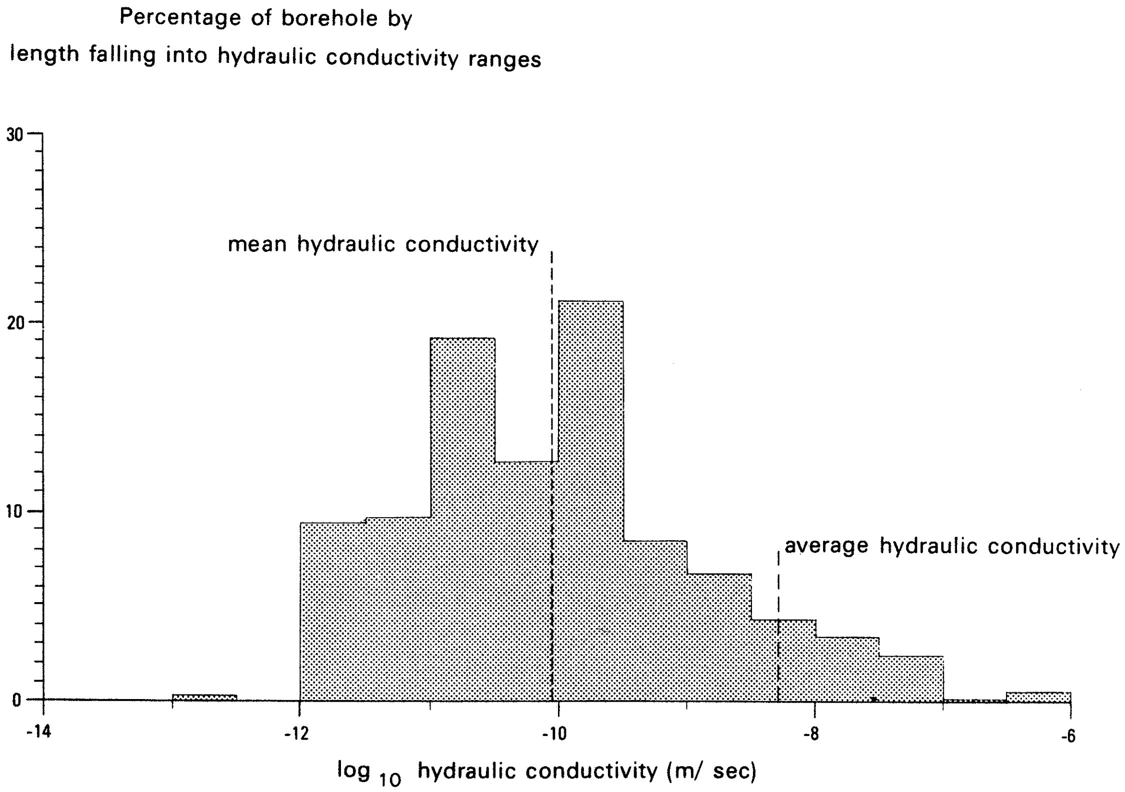


Figure 3.4.2 **The frequency distribution of the combined hydraulic conductivity results.**

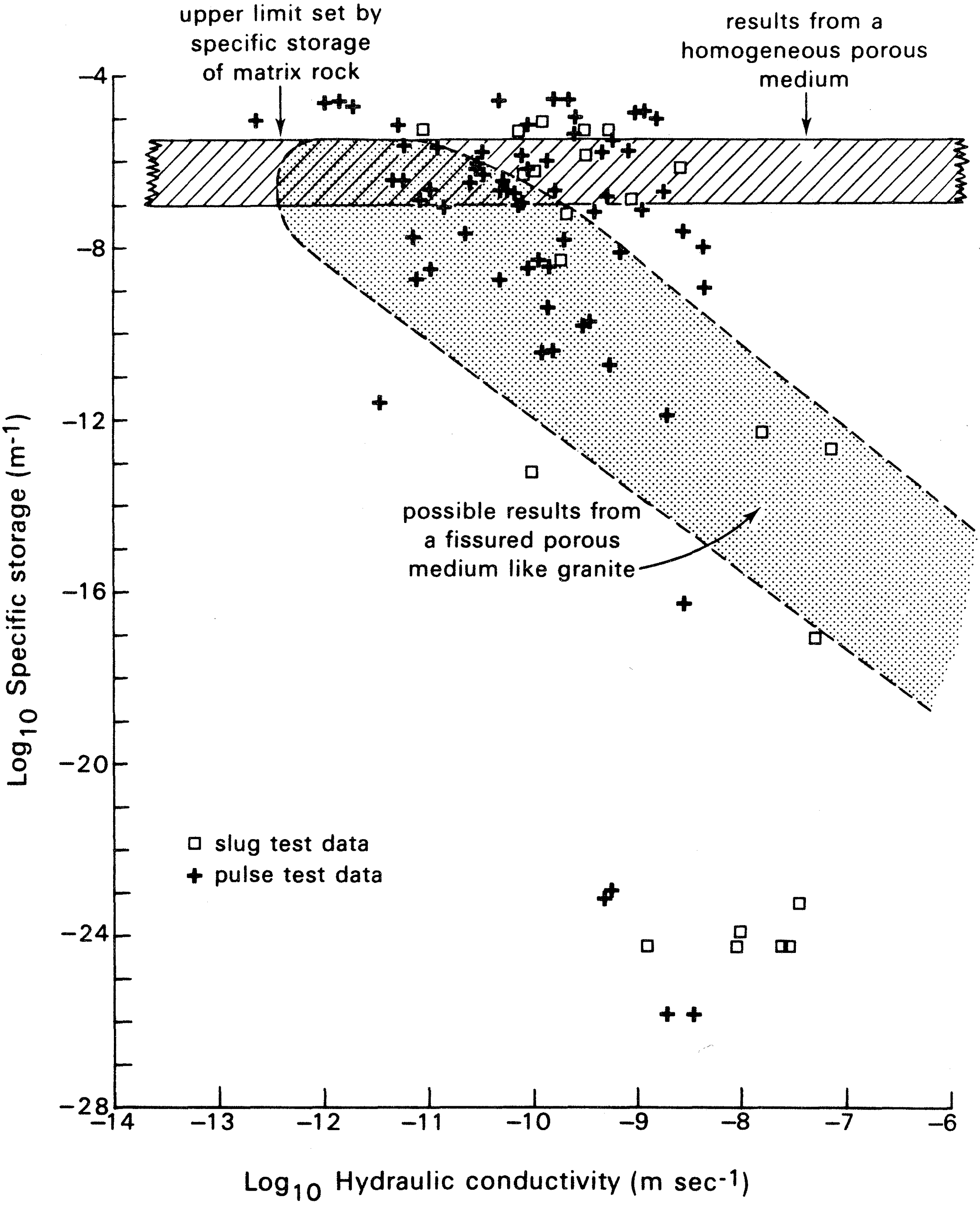


Figure 3.4.3 Slug and pulse test derived values of K and S_s from boreholes F3, F4, and F5 together with fields of expected results based on differing flow concepts.

Pulse tests and slug tests are transient methods which yield values of specific storage (S_s) as well as hydraulic conductivity (K). Since S_s reflects the storage involved in the test the results can be used to identify whether the rock seems to be responding either as a "large storage" porous medium or a "low-storage" fissure.

The properties of unfissured (matrix) rock are discernible as the hydraulic properties derived from the tests with the lowest values of hydraulic conductivity (K). The results indicate that the lowest value of K was measured at $2.3x10^{-13}$ m/s, but this was a single result. A more common result was around $1x10^{-12}$ m/s with associated specific storage (S_s) values between $1x10^{-6}$ and $1x10^{-4}$ m^{-1}. The 19 tests containing values of this type amount to a total of 143 m out of the 1282 m which were tested. Most of these tests were 10 m long so unfractured rock is quite common.

Knowing the likely properties of matrix rock it is then possible to examine all the single borehole slug and pulse test results to see if they indicate a consistent form of response. All the K/S_s results are plotted in Figure 3.4.3 together with the expected envelope of results if the responses were either of a porous medium or of radial flow within planar fractures in granite (i.e with $K=1x10^{-12}$ m/s and $S_s=1x10^{-6}$ 1/m). The results broadly indicate a response from a fissured porous medium. There are however a broad group of results with a S_s which is much higher than could be reasonably expected together with another group which is considerably lower than is possible with radial flow in a parallel-sided fissure.

These results can be explained by two possible phenomena. The first and most commonly used explanation is to assert that the results were affected by "skin". Skin is a catch-all well-testing term referring to altered rock properties (either increased or decreased K) in the immediate borehole surrounds. It is possible that either negative skin (increased K) or positive skin (decreased K) could have produced the observed results. Positive skin could explain the low values of S_s whilst negative skin could have produced the high K results. However the influence of skin in this manner is only possible if the pulse/slug test response is "transitional" in the sense of Black and Barker, (1987). This means when the storage of the skin zone is about equal to the volume of water used in the test. This is only realistically possible in pulse tests (see Black and Barker, 1987). However there are a considerable number of slug tests in the anomalous results so that it is difficult to imagine that skin is entirely responsible.

The second and more unusual interpretation of the cause of the discrepancy is the applicability of the assumed flow concept. In this case the assumed flow concept was of radial flow i.e. 2-dimensional. It can be shown that the low storage values can result from tests in which the flow was greater than 2-D and the high S_s values from tests approaching 1-D (i.e. flow in a pipe).

3.4.4.2 Crosshole tests

The crosshole testing was performed after the completion of the single borehole work. Given the length of the boreholes within the fan-array, a comprehensive series of criss-crossing "tomography style" tests was clearly impossible. A whole-borehole approach was also ruled out on the basis that it would yield nothing of the detailed geometry of the inter-borehole hydrogeology. The procedure adopted was to test in the region of broad zones identified by the geophysical techniques. In the end the bulk of testing centred on two significant geophysical features, termed Zone A and Zone C.

After testing for a period of about 15 weeks, 47 results had been obtained from 23 source-receiver pairs. This includes results on the same pair at different frequencies but does not include results where the there was no measured response to the source signal, in other words negative results. The tests were quite time consuming mainly because it was necessary to check all borehole responses to ensure that the signal was not being transmitted via other boreholes.

Zone A was the most extensively tested of all the geophysical zones by the crosshole sinusoidal technique. The places where responses were observed are shown in Figure 3.4.4a. It can be seen that Zone A has more responses in the southern side of the Crosshole site (i.e. the right hand side of the diagram). This may indicate that Zone A is bifurcating in this direction. It should be noted that F2 and F1 are very close together at the northern end of the site and extensive searching of F1 yielded no responses. If Zone A penetrates to the north of the site it is not conductive in that region.

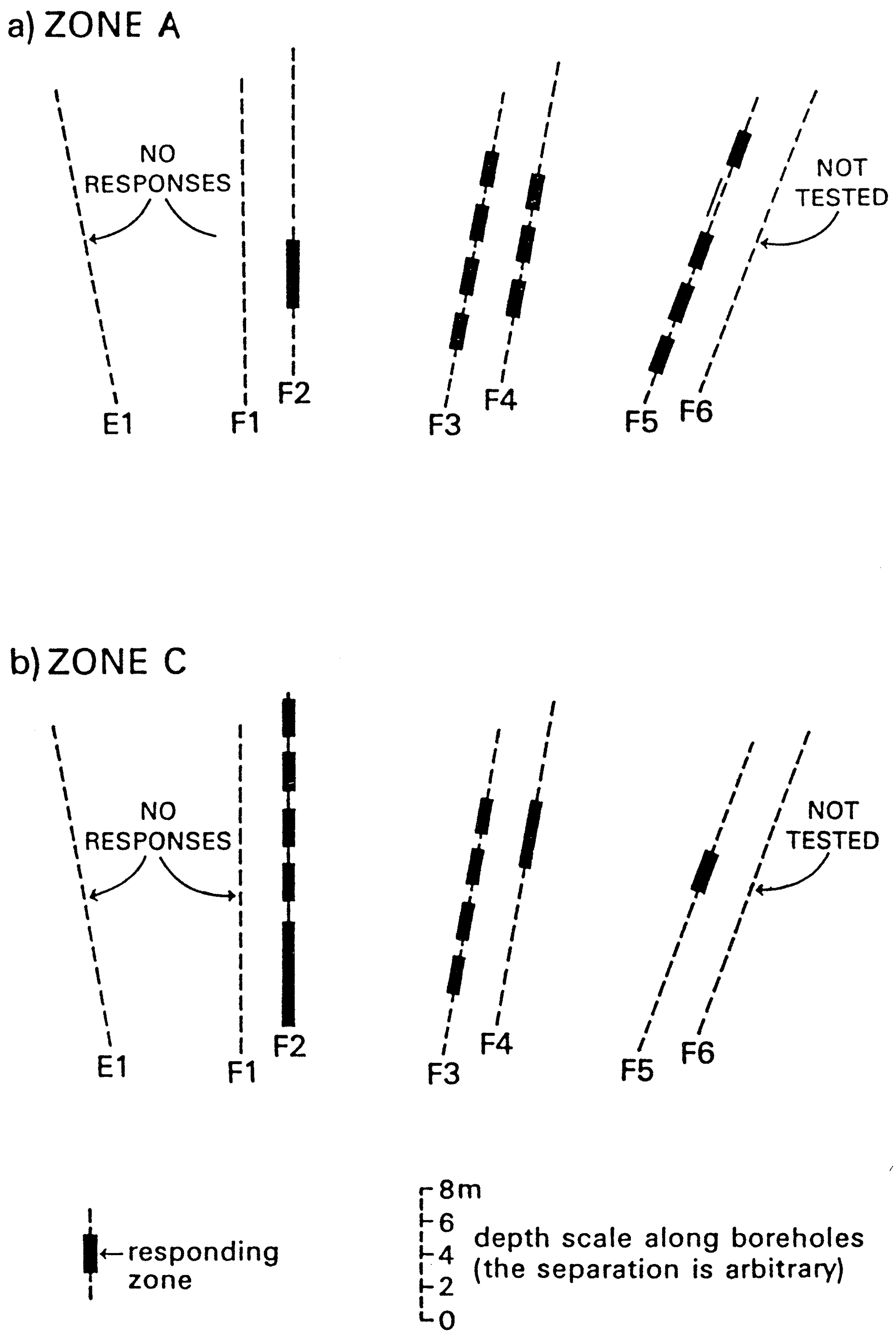


Figure 3.4.4 Pseudo perspective plan of the intervals where crosshole responses were measured: a) Zone A, b) Zone C.

The other zone which was extensively tested was Zone C (see Figure 3.4.4b). Since it intercepts the boreholes further from the instrument drift than zone A, the distances between the boreholes are larger. However, if anything, the number of responses seems to increase towards the north rather than the opposite in Zone A. In order to quantify the groundwater flow properties of the crosshole connections, it is necessary to interpret these data using some concept of flow. Essentially the geometry of the flow system is unknown. Possible geometries (see Black and others, 1986) included radial flow in a single fracture (2-D), spherical flow in a regularly fractured porous medium (3-D) and both with superimposed anisotropy. It is clear from the distribution of responding zones outlined above that spherical flow is inappropriate. Therefore an analysis based on flow in a pipe (1-D) was added to the range of possible flow concepts applied to the data (see Noy and Barker, 1987).

The first step in the interpretation was to examine the data sets for consistency. This meant that if response increased as well as decreased with changing frequency then entire source/receiver pairs were rejected. This resulted in three source/receiver pairs in Zone A and two in Zone C being thought appropriate for further analysis.

The next step in the interpretation procedure was to apply the 1-D and 2-D flow to the major response (the lowest frequency test) in each source/receiver data set. It was usually a 24 hour period test. A minimization technique (see Black and others, 1986) was used to derive the K and S_s which yielded predictions of head and phase lag in the receiver zone (based on flow in the source zone) closest to the measured values. The predictions were then checked for their appropriateness by examining the value of head (and its phase lag) which they predicted for the source zone. In all cases these predictions were found to be poor (see Table 3.4.2)

It was then decided that the problem lay in the flow concepts which had been applied. It was felt that these were too restrictive and that there was no real reason for the dimension of the flow concept to be an integer. This led to the flow concept of "fractional dimensions" in which it is conceived that flow occurs within a geometry that varies continuously between 1 and 3. Within this conceptual framework the effect of branching channels and fractures is to increase the effective dimension of the fissure flow system. For example as flow expands from a single channel into a fracture plane, via channel intersections, the dimension parameter increases from 1 to 2. The development of the fractional dimension analysis is detailed in Noy and Barker (1987). The overall effect is that the test is analyzed for geometry (i.e. the geometry is a variable where usually it is fixed). In finding the solution with minimum error using the fractional dimension approach, the dimension was increased from 1 to 2 in steps of 0.05. The results are summarised in Table 3.4.2.

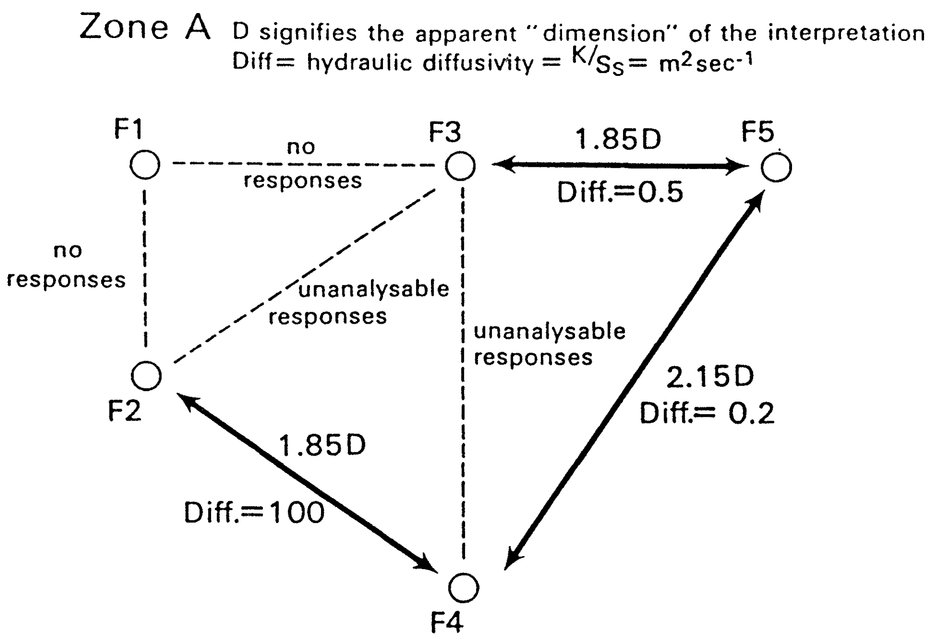
Table 3.4.2 Summary of fractional dimension interpretations. Source amplitudes are in m.

Source	Receiver	flow dimension	source amplitude meas.	source amplitude pred.	source phase lag meas.	source phase lag pred.
ZONE A:						
F4:53-56	F5:42-44	1	9.89	0.93	2.7°	48.7°
(period=1440 mins)		2	"	4.89	"	6.3°
		2.15	"	8.96	"	3.6°
F2:43-47	F4:53-56	1	9.74	5.8	9.0°	15.0°
(period=480 mins)		2	"	17.0	"	5.1°
		1.85	"	9.77	"	8.8°
F3:38-40	F5:38-40	1	9.66	2.05	11.0°	45.0°
(period=720 mins)		2	"	15.1	"	7.5°
		1.85	"	9.4	"	11.2°
ZONE C:						
F3:103-106	F5:93-96	1	7.28	3.26	18.6°	41.3°
(period=1440 mins)		2	"	19.8	"	6.0°
		1.7	"	7.37	"	14.9°
F2:116-119	F3:107-109	1	9.46	1.87	12.5°	45.0°
(period=720 mins)		2	"	15.6	"	6.6°
		1.85	"	9.17	"	10.4°

The improvement of the predictions based on fractional dimension compared to the fixed dimension cases is clear in the table. These interpretations were all based on the longest period in each set of results.

Using the previously derived dimensions, further predictions of phase lag and amplitude were made for the higher frequency tests in each data set. It was found that poor predictions resulted. The discrepancies increased with increasing frequency. It appeared that improvements could be achieved by again allowing dimension to be a variable. Of the two data sets in Zone A which contained variable frequency results, it was found that one was improved by reducing the dimension for matching higher frequency data and the other by increasing the dimension. The same result was derived from the responses in Zone C.

The results and their interpretation from the crosshole sinusoidal testing are rather complex. Firstly the results indicate that the Zones A and C are not simple planar fractures. Rather they seem to indicate that the zones are roughly planar systems of channels. It should be noted in the calculated fractional dimensions that Zone A has a generally higher dimension than Zone C. Considering that the distances between the source/receiver pairs are larger in the case of Zone C this probably indicates that Zone C is more sparsely channelled. The diffusivities derived from these interpretations (see Figure 3.4.5) are of the same order of magnitude except for Zone A:F2-F4. This was a particularly responsive zone where a slug test carried out in F4 was observed almost instantly in F2. There may be a more general trend for hydraulic diffusivity to decrease in Zone A towards the south. This is in the direction of increasing bifurcation (see Figure 3.4.4) Zone C shows a similar trend but with the reverse orientation.



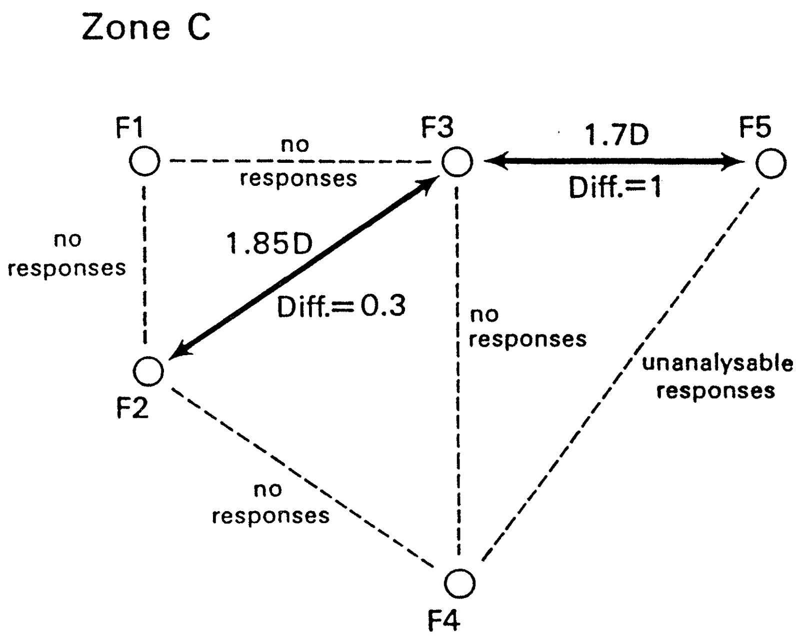


Figure 3.4.5 Schematic of fractional dimension results shown in relation to borehole layout: a) Zone A, b) Zone C.

4 GEOPHYSICAL MODEL OF THE CROSSHOLE SITE

4.1 RATIONALE BEHIND MODEL

The data from the investigations performed at the Crosshole Site are of three basic types:

- direct observations of geology and measurements of physical properties along the boreholes.

- remotely-sensed measurements of the physical properties of the rock in the space between the boreholes (obtained from radar and seismic measurements).

- measurements of the hydraulic properties of the rock immediately surrounding the boreholes based on assumptions concerning flow geometry.

It should be noted that the hydraulic measurements provide only limited information on the geometry of the water flow paths. In fact, the derivation of hydraulic properties (such as hydraulic conductivity and specific storage) from the field measurements is dependent on knowledge of the flow geometry.

Considering the need of the hydraulics for geometrical information, it was considered relevant to construct a geometrical model based essentially on the radar and seismic measurements. The model describes the extent of regions with anomalous physical properties and the magnitude of these properties. In the construction of the model the radar and the seismic data have also been correlated with data of similar type obtained from the single-hole investigations.

Since the model produced is based essentially on the radar and seismic investigations, its features reflect the position and extent of radar and seismic features. These features observed in the radar and seismic data are to a first approximation related to the fracturing of the rock. For example, increases in water content associated with fracturing will cause a localised change in the dielectric constant and electrical conductivity. These changes in electrical properties are then the features observed by the radar. Fractures also cause a decrease in the mechanical stiffness and strength of the rock which, in turn, decreases P and S-wave velocities. These decreases are then observed by the seismic method.

However, the radar and seismic methods yield continuously varying fields of electrical and mechanical properties. These are interpreted in the basic geometrical model as two types of rock: heavily fractured and averagely fractured. Hence the geometrical model is a binary one in which regions of heavy fracturing are designated as fracture zones emplaced within background rock. The division between fracture zones and background rock is based on combining the regions of geophysical anomaly seen in tomograms with the occurrence of fractures observed by radar reflection.

4.2 EXAMPLES OF RADAR AND SEISMIC RESULTS

Both the radar and the seismic methods have been applied in reflection and tomography modes. The radar reflection data constitute a comprehensive data set while there are only a few seismic reflection results. Tomographic results have been obtained between roughly the same boreholes with both methods. The tomograms based on radar and seismics are easy to compare since they are obtained, analyzed and presented in the same way. The only difference between them results from their dependence on different physical properties. The relationship of these properties to the fracturing of the rock is similar.

The tomographic reconstruction of crosshole data yields maps of the distribution of the relevant physical properties in the plane between two boreholes (see Figures 4.1 to 4.4). In these tomograms the darker color indicates properties which are indicative of increased fracturing of the rock, i.e. reduced radar and seismic velocities and increased radar attenuation. The tomograms "F1-F6 (radar)" and "F5-F6 (seismics)" represent two sides of the pyramid outlined by the boreholes. The third section, represented by "F4-F5 (radar)" and "F4-F5 (seismics)" cuts through the interior of the pyramid. The F4-F5 section has been measured both by radar (see Figure 4.3) and by seismics (see Figure 4.4). The radar tomogram is obtained from inversion of radar attenuation data while the seismic tomogram shows the distribution of seismic velocity. The similarity of the results is striking. The same major features are found in the same locations and have a similar form. A general agreement between the seismic and the radar tomography results is found over the entire Crosshole Site.

The tomographic interpretations agree in a second important manner. In places where measured sections intersect, we find that the anomalous features occur at the same locations. These intersections occur both along boreholes and along lines in the region between boreholes. An example of the agreement between both method and section is the intersection between "F1-F4 (seismics)" and "F4-F5 (radar)" (see Figure 4.5). This intersection occurs along the line of the borehole F4 in which the seismic measurements were spaced at effective spacings of 5 m compared to the radar's 4 m. The agreement is surprisingly good. The second type of intersection is like that between "F1-F6 (radar)" and "F3-F4 (seismics)" (shown in Figure 4.6). The line of intersection actually occurs approximately in the centre of the investigated region. Again the agreement is extraordinary and gives confidence that the geophysical anomalies depicted by the tomographic interpretation of crosshole data are real and correctly positioned in space.

From the tomograms we can see that the darker parts, which represent increased fracturing, form approximately planar regions or zones. However, it is also evident that the geometry of these zones is irregular and that the magnitude of the geophysical anomaly varies within them.

Reflection measurements give information of another type. Reflections are caused by changes in properties and are not very sensitive to the absolute value of these properties. It is apparent that in plots of radar reflection results (see Figures 3.1.5 and 4.7) zones of anomalous geophysical properties are seen as essentially linear features. Some variations in reflectivity and deviations from a straight line can be observed. It is also likely that these linear features represent the edges of anomalous regions so that where they have significant thickness both edges may be seen by the method. This sometimes occurs.

Interpretation of radar reflection plots is not as straight forward as the interpretation of tomograms. One problem is that the radar reflection plot does not represent a specific plane in space due to the cylindrical symmetry of the antennae. The orientation of zones can however be deduced if the reflection data from several boreholes are combined. (The interpretation of single-hole reflection data is described in Section 3.1.)

As the reflection plots yield information of a different type to that from the tomograms, it is difficult to make a direct comparison between these results. The reflection data give the position and angle of intersection of the edges of zones with the boreholes. In general, there is good agreement between reflection and tomography data with respect to the location of the major zones. However, because the reflection measurements are more sensitive to changes in electrical properties than the transmission measurements, more zones are seen by reflection than transmission (i.e. tomography).

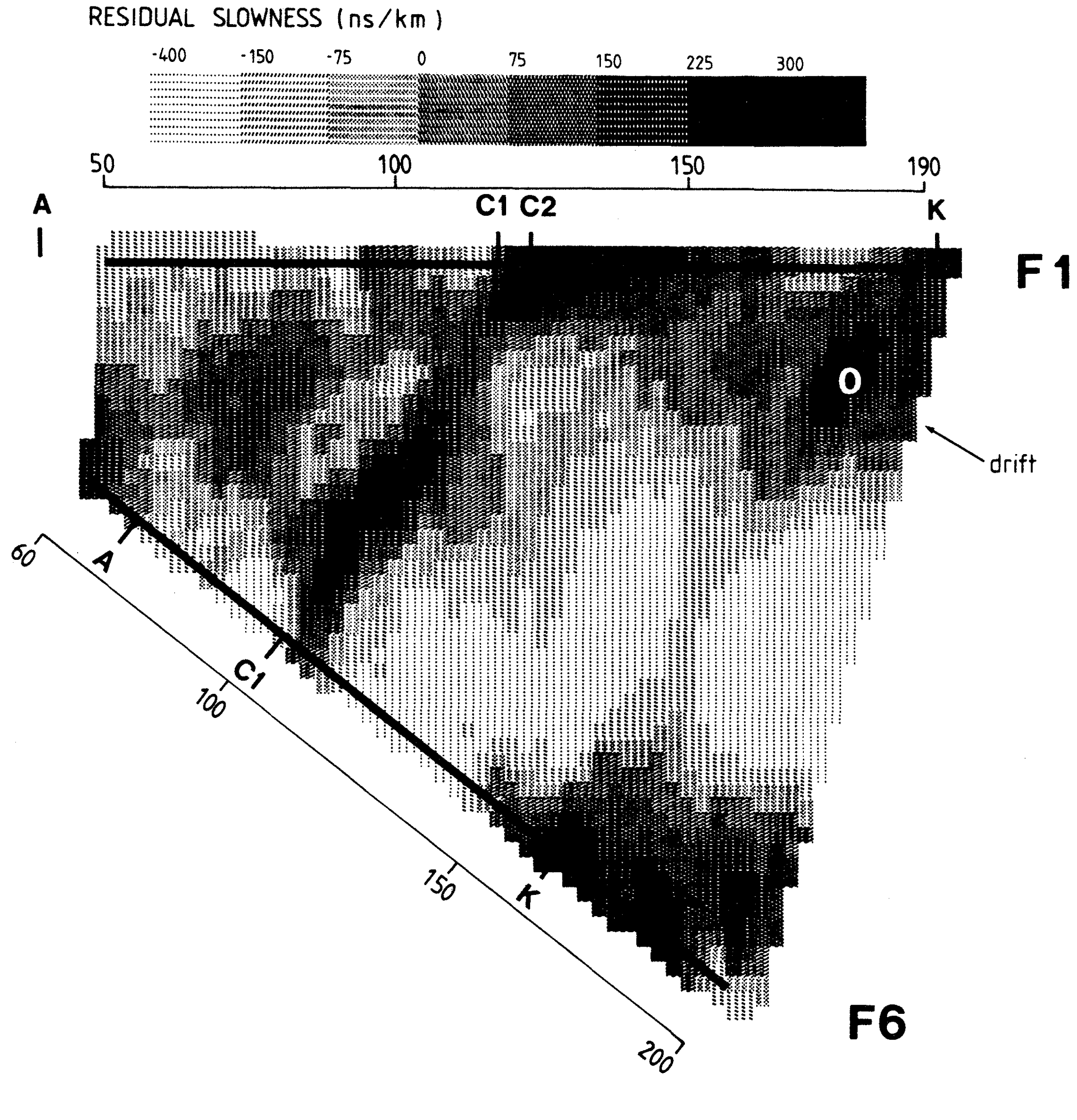


Figure 4.1 Tomogram obtained from inversion of radar travel time data obtained from crosshole measurements between boreholes F1 and F6.

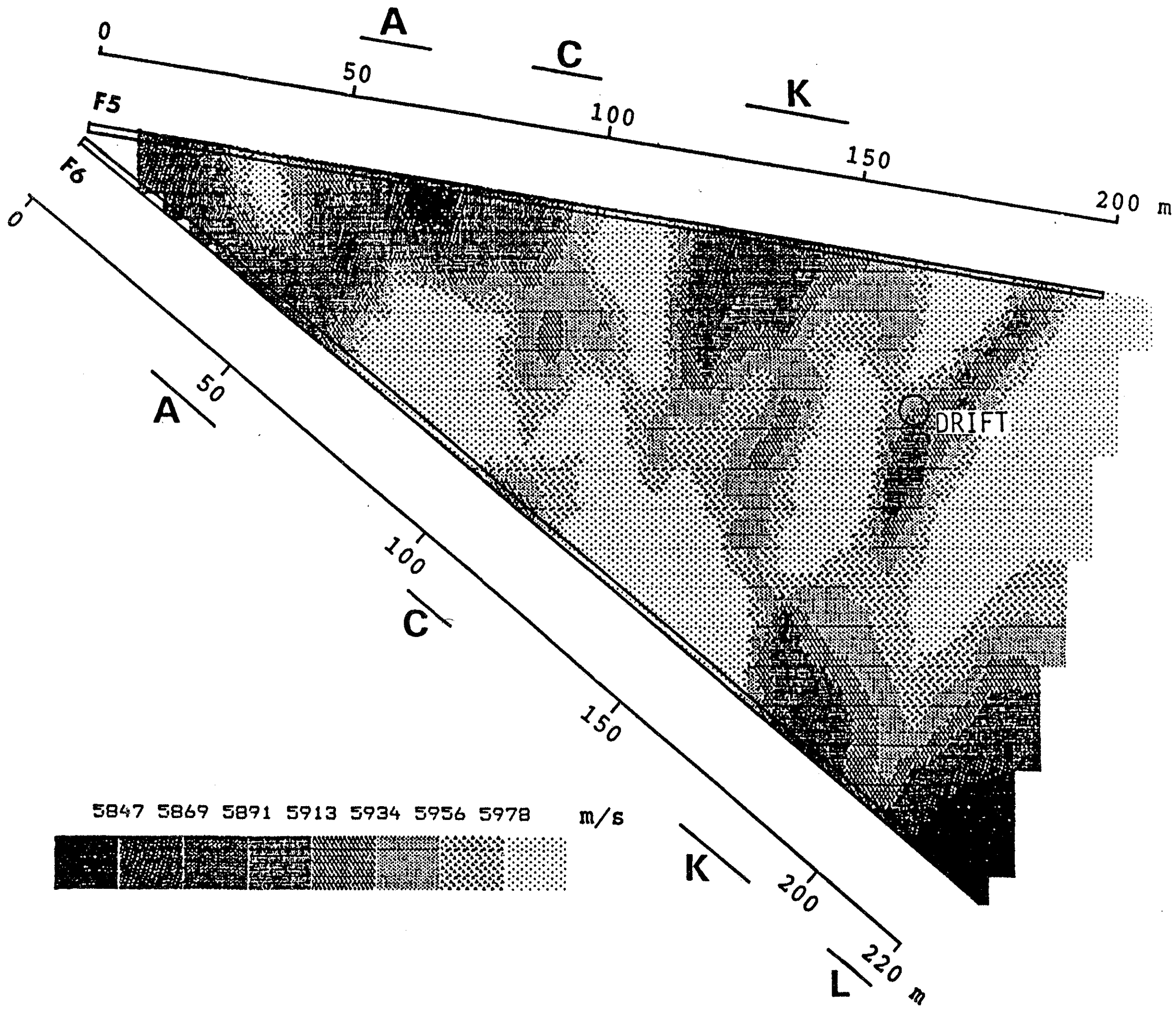


Figure 4.2 Tomogram obtained from inversion of seismic P-wave travel time data obtained from crosshole measurements between boreholes F5 and F6.

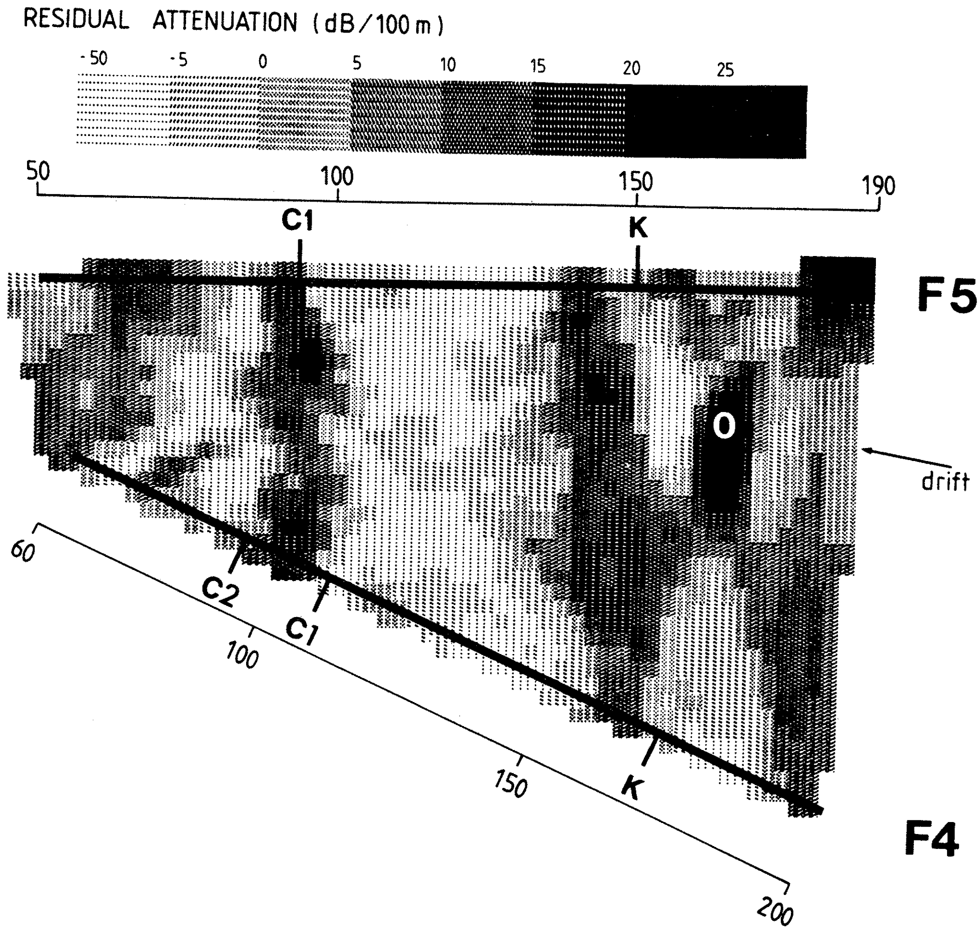


Figure 4.3 Tomogram obtained from inversion of radar amplitude data obtained from crosshole measurements between boreholes F4 and F5.

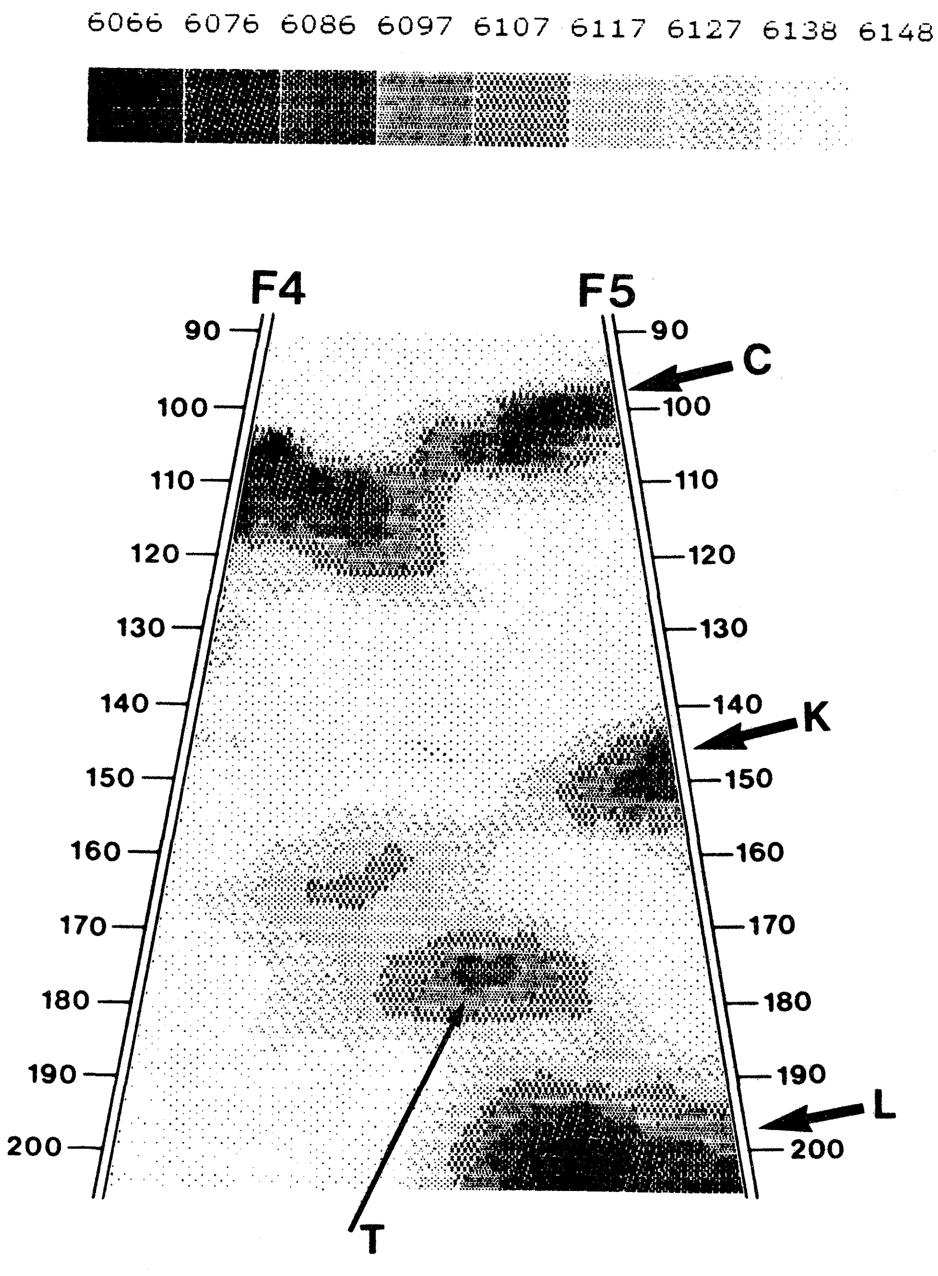


Figure 4.4 Tomogram obtained from inversion of seismic P-wave travel time data obtained from crosshole measurements between boreholes F4 and F5.

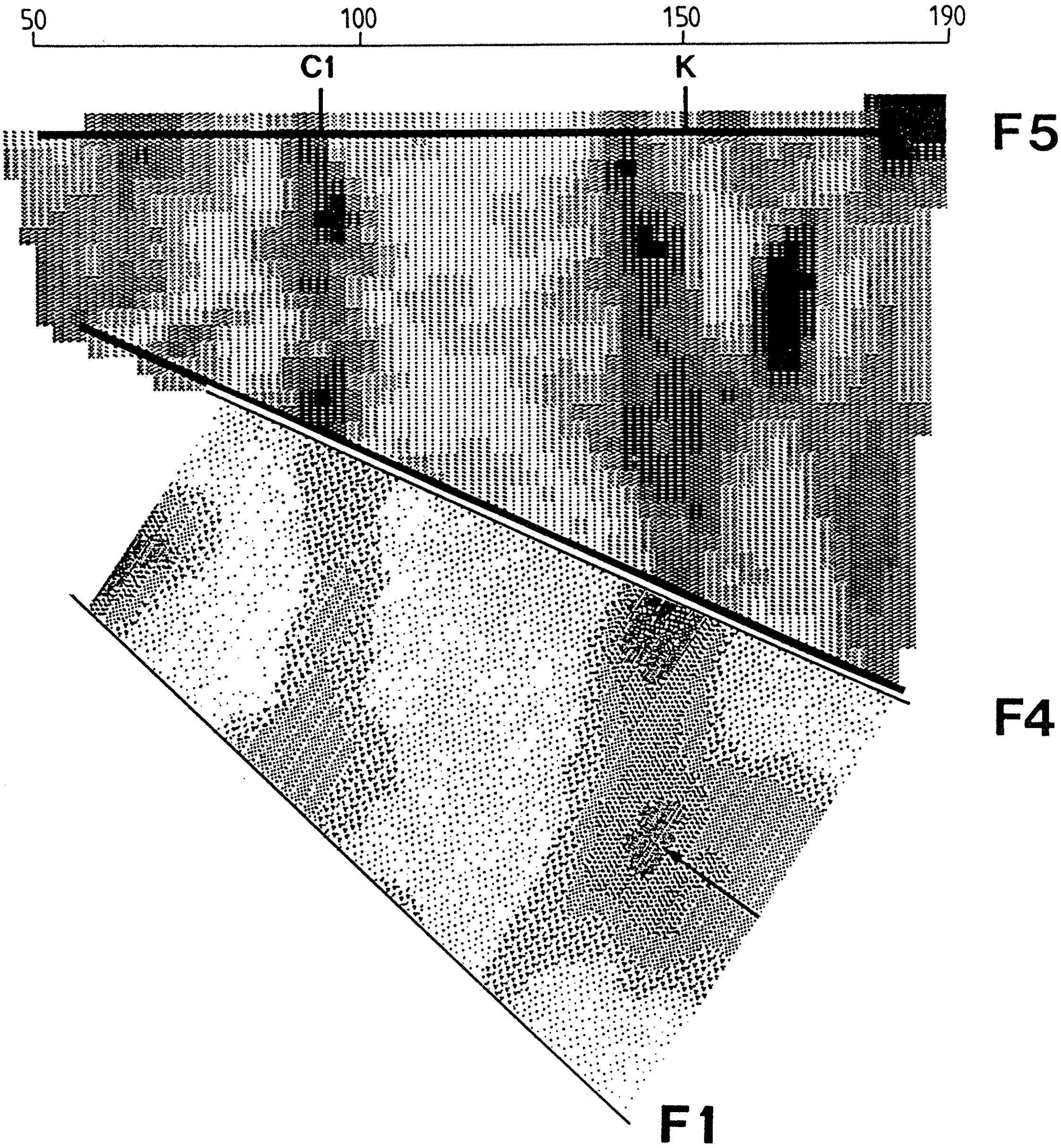


Figure 4.5 Tomograms obtained from inversion of seismic travel times (F1-F4 section) and radar amplitudes (F4-F5 section). There is excellent agreement in the location of the anomalies along the intersection line common to both sections (borehole F4).

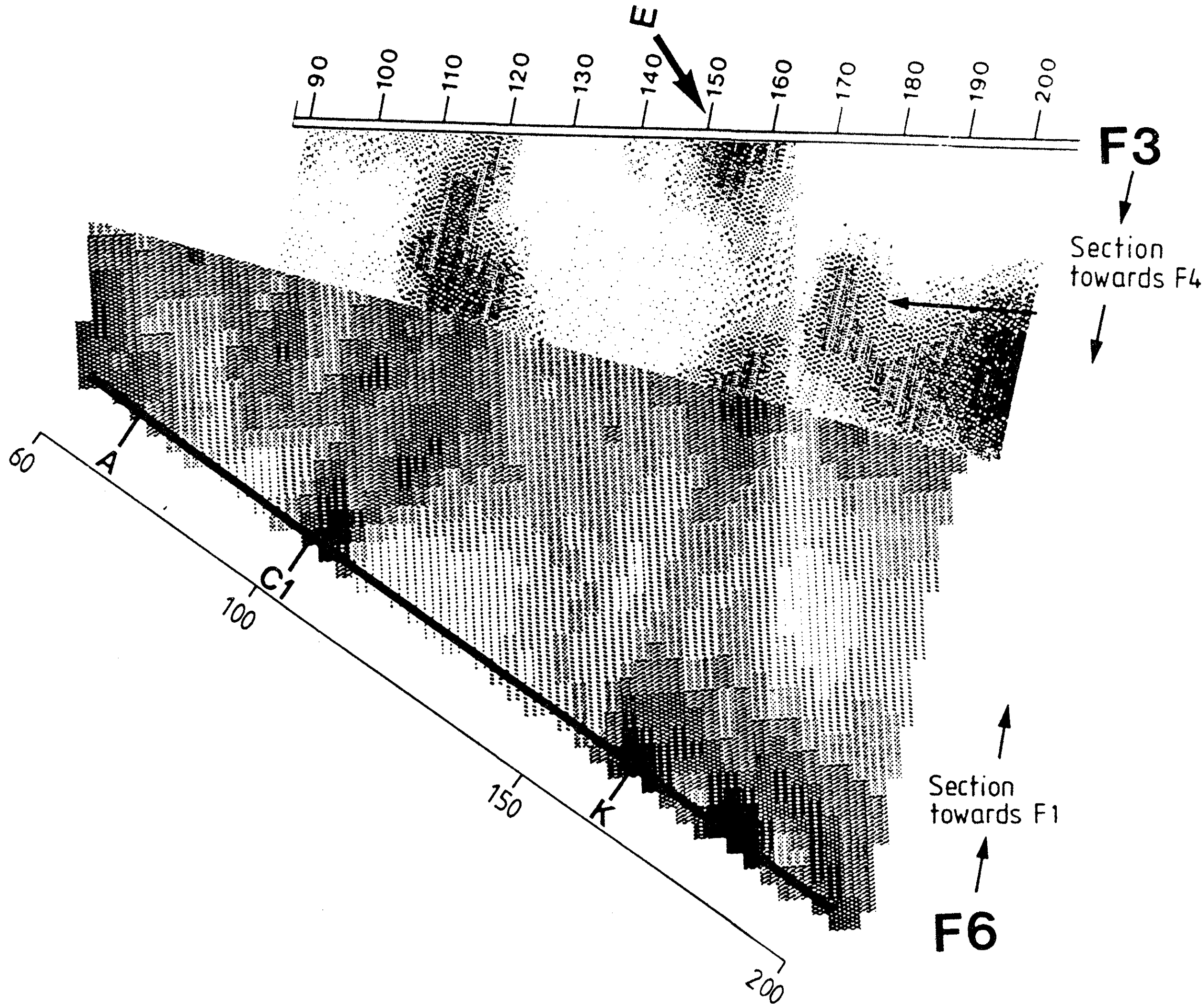


Figure 4.6 Tomograms obtained from inversion of radar amplitudes (F6-F1 section) and seismic travel times (F3-F4 section). The intersection line common to both sections occurs approximately in the middle of both sections.

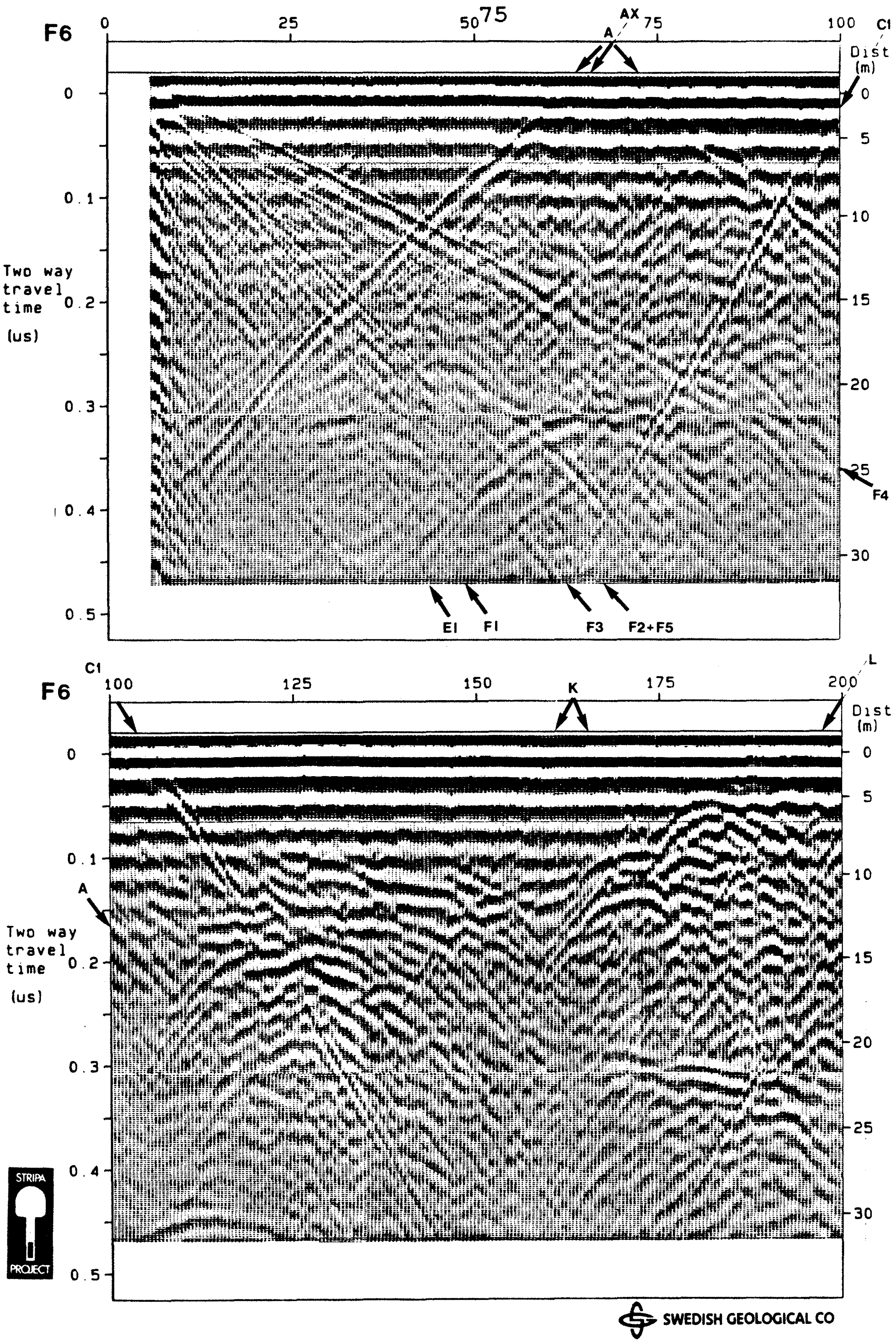


Figure 4.7 Singlehole radar reflection results from borehole F6. Measurement made with a center frequency of 60 MHz.

4.3 DIVISION INTO BASIC AND EXTENDED MODELS

Two models of the Crosshole Site have been devised. They are termed the "Basic Model" and the "Extended Model". The basic difference between the two is that the Extended Model contains all the features of the Basic Model plus some additional (fracture) zones.

The Basic Model contains the most significant zones which have been identified as large anomalies in both the radar and the seismic investigations. These zones have also given significant responses in the single-hole investigations. The existence and location of these zones is considered to be well established and therefore the Basic Model should be highly reliable.

The Extended Model contains, in addition to the zones included in the Basic model, two other types of zones. The first type of extra zones was identified by only one of the geophysical methods. This results from the differing coverage of the region by the different techniques and includes zones outside the pyramid of boreholes inferred from radar reflection data. The second type is zones which produce smaller anomalies compared to the zones contained in the Basic Model.

The density of data varies within the Crosshole site. The highest density occurs between all the boreholes in the depth interval 80 m to 200 m. In this region the geophysical data set is complete, including tomography and reflection analysis of both radar and seismic data. Radar reflection data have been obtained from the entire length of all the boreholes and this has given information even outside the pyramid outlined by the boreholes.

4.4 THE BASIC MODEL

The Basic Model includes zones A, C, K, and L which are observed as prominent features by all geophysical methods. The layout of these zones is depicted in Figure 4.8. from which it is evident that they form two sets characterized by their orientation. This is seen more clearly in a Wulff plot of the normals to the zones (see Figure 4.9). In Figure 4.9 all zones from both models are plotted. The zones C, K, and L are essentially parallel, the strike is NE and the dip is steep towards NW. Zone A has a different orientation. The strike of A is NNE and the dip is steep towards SW.

The positions of intersection of the zones with borehole F3, which lies in the centre of the investigated region, are given in Table 4.1. The orientation of these zones is also given. The table also includes the zones of the Extended model and it can noted that these zones have an orientation similar to zone A (see also Figure 4.9).

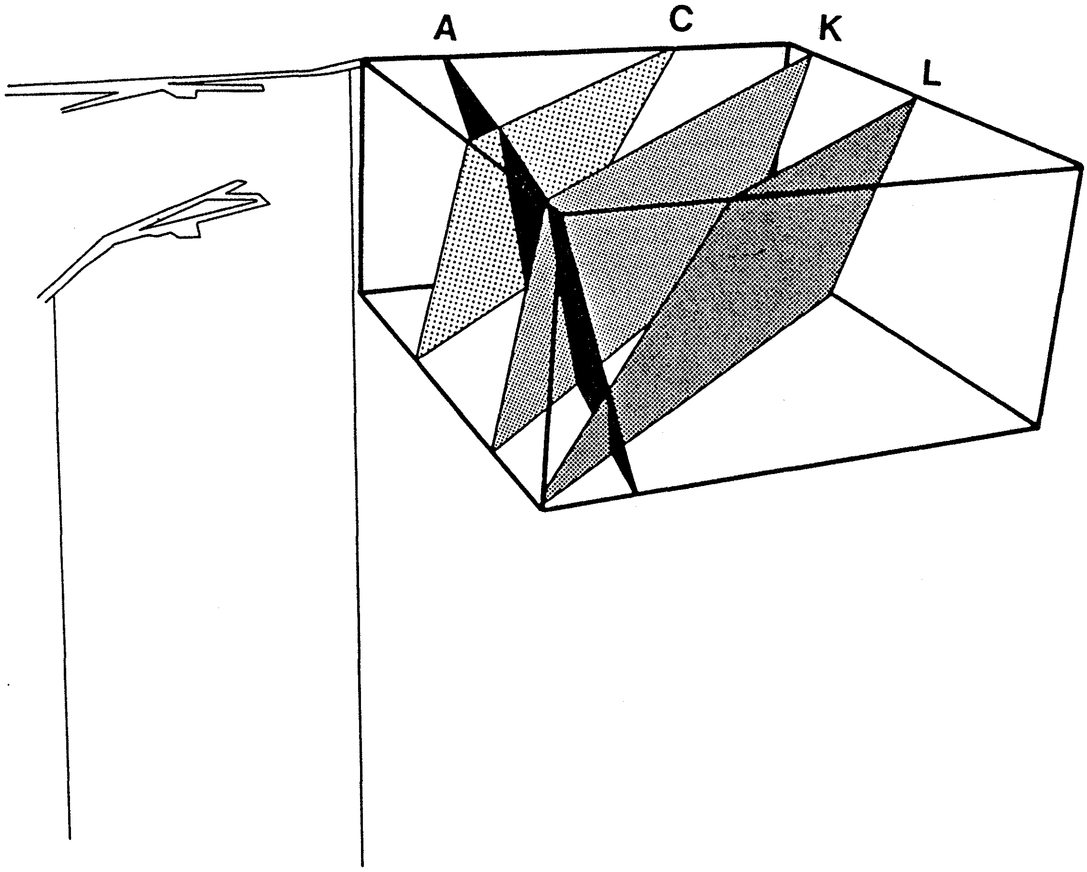


Figure 4.8 Perspective view of the zones included in the Basic Model.

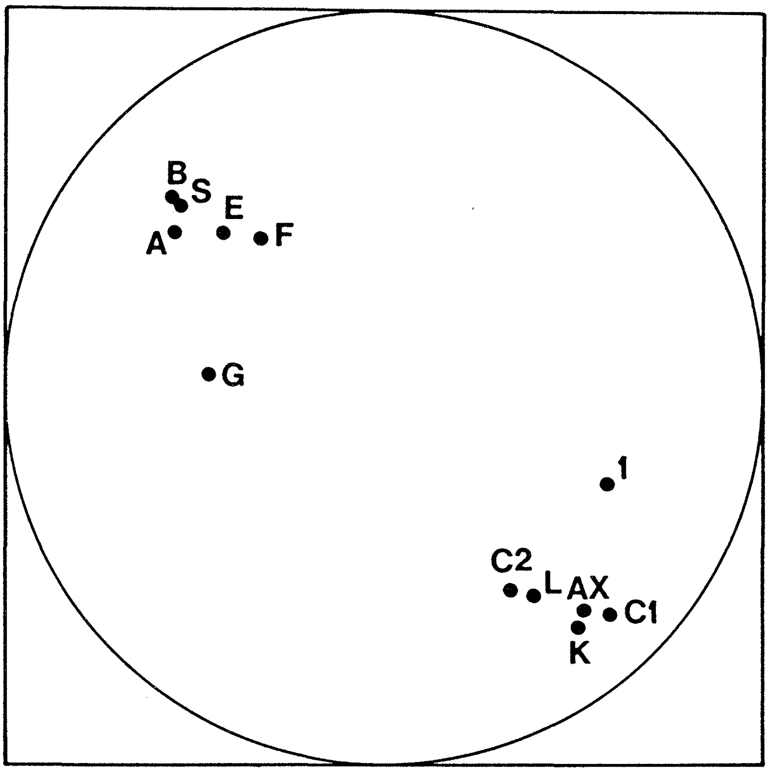


Figure 4.9 Wulff plot of normals to all the zones contained in both the Basic and the Extended Models.

Table 4.1 Location and orientation of fracture zones contained in the Basic and Extended Models of the Crosshole Site. Orientation is given with an accuracy of 5^{o}.

Zone	Intersection with F3 (m)	Dip (deg)	Strike (deg)
<u>Basic Model</u>			
A	39	70	10
C	107	70	230
K	170	75	230
L	240	70	235
<u>Extended Model</u>			
Site zone	-5	70	40
1	14	55	200
E	153	60	40
F	154	55	50
G	220	50	5

Owing to the variable data density, the data set supporting the Basic Model is not the same for all zones. Zone C is the zone which is based on most data because it happens to occur where all methods have been applied and given useful data. Zone A is well described by radar reflection and hydraulic data while zone K is well described by the geophysical methods but lacks any crosshole hydraulic data. The data describing zone L are limited because it occurs in a corner of the investigated pyramid.

A description of the most significant characteristics of the zones as they have been found by the different methods is given below.

Zone A

The orientation of zone A derived from the radar reflection data is variable suggesting that it is undulating in some way. The pattern of reflections is more complex in the plots from F5 and F6 suggesting that zone A may be intersected by some other zone or that it splits up into a few minor zones. Seismic tomography detects Zone A only in section F5 - F6 where it is one of the most prominent features. It is not detected in any of the other crosshole sections because it lies between the instrumentation drift and the start of crosshole seismic measurements. Judging from both reflection measurements and tomography, Zone A is about 10 metres thick.

Zone A characteristically contains two varieties of breccia healing, a coarse calcite-fluorite healed breccia and a dense epidote-chlorite healed one. In some parts the breccia contains angular granite fragments up to 1 cm in size. The zone is red coloured and moderately fractured. Cavities with idiomorphic crystals are common in the core from all borehole intersections with Zone A except F6. In all boreholes except F1 the temperature log indicated water inflow where Zone A cuts the open borehole.

Zone C

Zone C is clearly seen by radar reflection from all boreholes. It is exceptional because reflections of similar strength take place from both sides of the fracture plane; usually one side tends to dominate. Zone C is seen as one unit in F5 and F6 but in the other boreholes it appears to have split into two with an included angle of about 10 degrees. The weaker reflector of the two planes has been named C2. Reflection seismic tests show that zone C bifurcates in at least two nearly parallel subunits.

The apparent thickness of zone C is nearly 10 m which compares well with the resistivity log. The resistivity values were also used to estimate the radar reflection coefficient and the measured and calculated values agree fairly well.

Zone C also shows up very clearly in the tomograms. Tomography does not detect the bifurcation, but displays variations in thickness. The widening of the zone towards F1 in the seismic section F4 - F1 could include both arms of a bifurcation. In all tomograms Zone C is clearly visible as a straight and well-defined feature. The average seismic velocity contrast is low but it is likely that the actual seismic velocity inside the zone is less than the values inferred by tomographic processing. In tomography, the whole zone, which also contains portions of unaltered rock, is averaged. Velocities within the zone are lowest around F1 and F3 and highest around F5 and F6. Hence we would expect Zone C to be more important in the northern part of the site (around F1 and F2) than in the southern part (around F5 and F6).

Zone C is one of the most strongly tectonized and brecciated zones encountered in the boreholes. The breccia is healed by a matrix of complex nature which consists of quarzitic material, ferrogeneous material, calcite-fluorite healing, epidote healing, and chlorite healing. In most of the boreholes the breccia contains large fragments up to 1 cm in size. Zone C is strongly fractured in F2, F3, and F6 while there is no increase in fracture frequency relative to the background rock at the intersection of the zone with F5. Cavities with idiomorphic crystals, mainly calcite and fluorite, are found in core from the boreholes F1, F3, and F5. The temperature log has indicated water inflow associated with the zone in all boreholes except F4. The character of Zone C at its intersections with all the boreholes is evident in the single-hole logs (Figure 4.10).

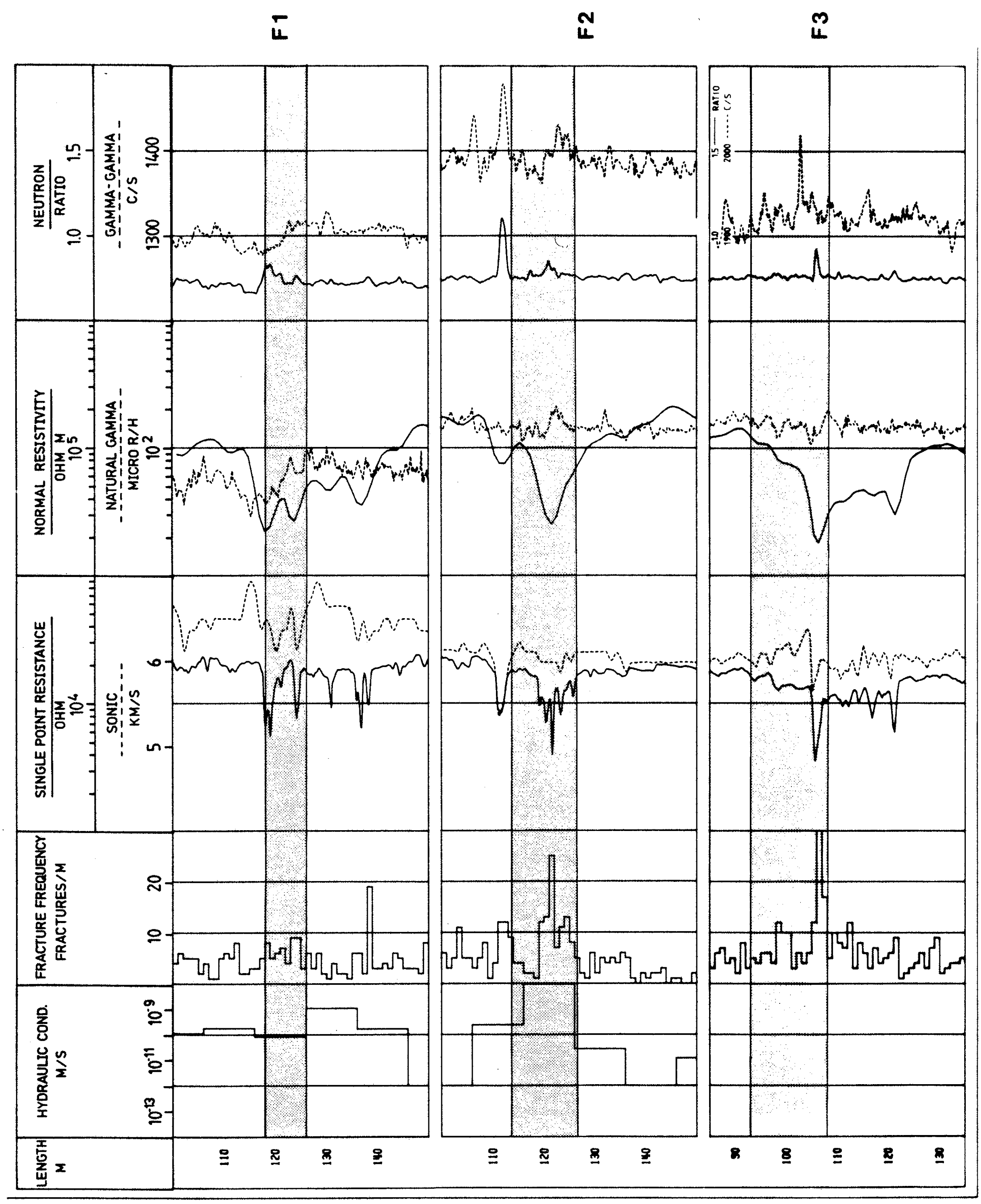


Figure 4.10a Single-hole logs of the intersection of Zone C with the boreholes.

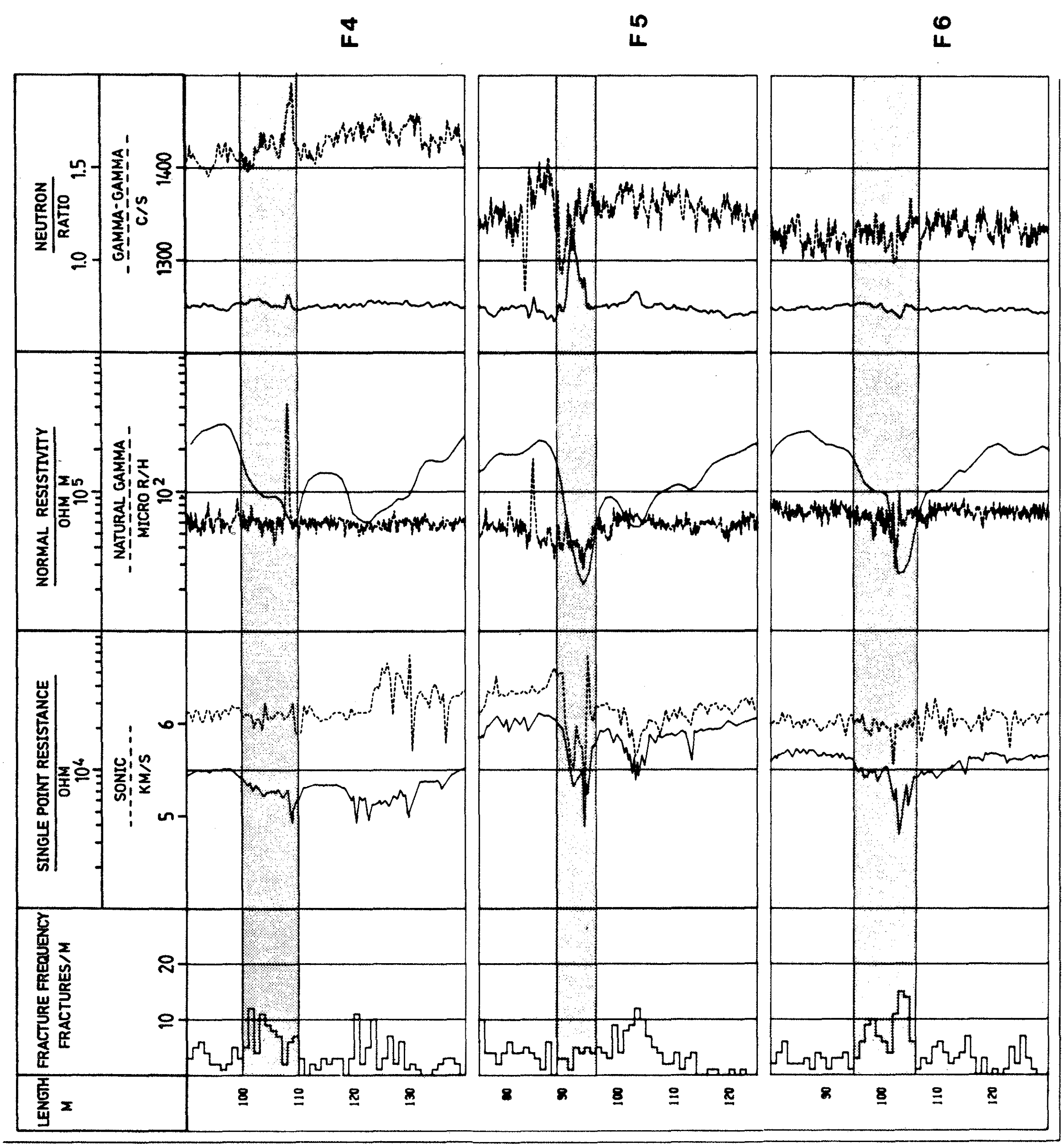


Figure 4.10b Single-hole logs of the intersection of Zone C with the boreholes.

Zone K

Zone K was not described as a separate unit by the single-hole surveys, probably due to its irregular character. It may well be that in the geological description this zone is represented by parts of units "E" and "F" (Carlsten et al. 1985). Within the volume of the site it appears as a series of low velocity features which connect some of the assumed borehole intersections of units "E" and "F" detected by reflection radar. It is difficult to assign to this zone unambiguous values for dip and strike. Radar reflections are most prominent in F4 and F6 but in the last case the reflections are strongest some distance away from the borehole. In the other boreholes, the reflections are strong only in a few places although the reflecting areas are not too distant from each other. On the other hand Zone K is clearly seen in some of the radar tomograms but its appearance varies considerably.

In the seismic section F4 - F1 zone "K" runs parallel to zone C and exhibits a larger velocity contrast. The velocity is lowest near where the zone intersects F4. A similar distribution is noticed in the F4 - F6 seismic tomogram. This distribution of low velocity where Zone K cuts F4 is also seen in the F1 - F6 seismic section which crosses close to F4. In this section Zone K is detected as an elongated spot centered on F4. Two low velocity patch-like features corresponding to the position of zone K can be seen in the section F4 - F5. In section F4 - F3 a more complicated pattern results from the coincidence of zone K with zone E, the old drift and other local anomalies. It is apparent that a planar zone K could not explain the pattern observed. More likely, this feature consists of a series of elongated patches, with length dimensions varying from 20 to 60 m. When seen at a large enough scale these patches coalesce to form a generally planar feature.

Zone K is most strongly fractured at its intersection with F4 while the fracture frequency in the other holes is moderate. The zone is red colored and brecciated and there are fractures which contain idiomorphic crystals. There are no temperature log anomalies associated with this zone.

Zone L

Zone L is a broad zone, more than 20 m wide, situated at the very bottom of the measured area, with a strike and dip out of the region. It is therefore only seen in two of the boreholes and not so well established as the previous zones. The radar reflections are strong and indicate an intensely fractured zone nearly parallel to C and K. This feature has the highest seismic velocity contrast of all anomalies detected at the Crosshole Site. A large amount of the recorded tubewaves have been associated with zone L.

Zone L has a high fracture frequency at its two intersections with the boreholes. The zone is red coloured and brecciated but the tectonization is not as significant as for the other zones in the Basic model. The zone is associated with temperature log anomalies at the two intersections indicating that there is water flow between the zone and the boreholes.

4.5 THE EXTENDED MODEL

Tomographic analysis determines the existence of fracture zones quite efficiently in the plane bounded by the two measurement boreholes. However, structures outside the plane between the boreholes or parallel to them cannot be observed. Thus some zones are only observed in radar reflection measurements.

The Site Zone

The Site Zone passes through the instrument drift from which the boreholes of the Crosshole site were drilled and therefore offers an opportunity to observe a radar reflector directly. The width of the fracture zone in the drift is 10-20 cm. It is seen in all single-hole as well as some crosshole radar reflection measurements. Based on its orientation it is a member of the same set of fracture zones as Zone A.

Zone E

Zone E is seen from most boreholes as a rather well defined though not always strong radar reflector. Its orientation, checked against crosshole reflection methods, places it in the same group with zone A and the Site zone. Due to the small angle with which it intersects the boreholes, zone E is generally difficult to detect by tomographic analysis. The seismic section F3 - F4 has a more favorable orientation with respect to this zone and contains a low velocity feature extending from the middle of hole F3 downwards at around 40 degrees. There are no tubewaves associated with this zone.

Zone F

Zone F is located by radar reflection measurements near zone E and with approximately the same orientation. The uncertainty in the direction is larger than in the previous cases since there is some confusion between the reflections caused by zones E, F and K in some boreholes.

Zone G

Zone G is a relatively strong radar reflector even further out from the site. It appears to have an orientation similar to that of A, E and F even though the determination is uncertain since so little is seen of the reflection pattern.

Zone 1

There are many other indications of fracture zones which are less prominent than those previously discussed. Close to the start of the boreholes, the core logs indicate a rather weak (moderately tectonized, variably fractured) zone called Unit 1 with an orientation similar to C, K and L. Only a few very weak radar reflections from this zone have been found in the radar pictures.

4.6 OTHER FEATURES

The old drift passing through the measurement volume is a very good reflector of radar pulses. Since it is nearly orthogonal to most boreholes it behaves almost like a point reflector in these measurements. Most of the energy is scattered from the point closest to the boreholes. The old drift is also clearly seen in all seismic velocity and radar amplitude tomograms. In the radar velocity tomograms it is hardly seen because the air it contains is a high velocity medium.

A rather unusual zone of very high porosity (9%) was observed in the core from F1 and F2. It is named Zone B but it has only limited extent. It contains numerous cavities, has a red colour and is intensely altered and highly fractured. It can be seen in radar reflection measurements from F1, F2, F3 and E1, often appearing as a band of two or three reflections. Zone B is also indicated by a low velocity anomaly found at the very top of the seismic section F1 - F4. Tubewaves associated with this zone have also been recorded in borehole F2.

A weak radar reflector named Zone AX has also been identified which intersects F3 at a borehole depth of 56 m and has an orientation similar to C, K, and L. In some of the holes this zone is associated with increased fracture frequency and weak resistivity anomalies.

There are some indications of zones oriented parallel to the boreholes. The reflection measurements are then difficult to correlate because of the uncertainty in the borehole intersections. Similarly zones with this orientation could be expected to show up weakly in the tomograms. However, no horizontal zones of similar thickness and contrast in properties as those belonging to the Basic Model are believed to exist.

Some other features are detected by seismic methods. Sections F1 - F4 and F3 - F4 map a low velocity zone near borehole F4 at 140 m depth. It is not found in other boreholes. Another zone, parallel to the L zone, is also found at depths of 200 m in F5 and 170 m in F6.

4.7 BACKGROUND ROCK

In the radar reflection measurements sharp reflectors are found at fairly regular intervals. This indicates that the rock mass between the reflectors is relatively homogeneous. The large radar ranges obtained also indicate that the density of reflectors is relatively low as a high density would lead to rapid scattering of the radar energy and subsequently short ranges.

The tomograms are less sharp and also provide quantitative values for the electric and mechanical properties of the rock. The results show that the velocity contrasts between background rock and the fracture zones are relatively small. The rock properties derived from the seismic tests fall in the range:

Average P velocity:	6100 m/s - 6500 m/s
Average S velocity:	3600 m/s - 3700 m/s
Average Young's modulus:	88 GPa - 92 GPa

The average P wave velocity for competent rock has been found also by sonic logging to be between 6100 m/s and 6500 m/s (Carlsten et al. 1985). These values correlate very well with the crosshole seismic results. A small but systematic variation was also noticed in the sonic log velocity in different boreholes. This indicates that the granitic mass of the site may exhibit seismic velocity variations not connected with fractured zones. This variation was also seen in the crosshole seismic measurements, e.g. towards borehole F6. However, this variation should be placed in the context of very small variations of seismic velocity observed throughout the site. These amounted to less than 8% difference between the minimum and the maximum recorded velocities.

The average properties of the background rock obtained from the radar tests are:

Average radar velocity	120 m/µs
Average attenuation at 22 MHz	28 dB/100 m
Average attenuation at 60 MHz	42 dB/100 m

In the discussion of fracture zones versus background rock it is essential to have an idea of the contrast in properties. The contrasts between the properties of the zones included in the Basic Model and those of the background rock have been estimated from the tomograms and are listed in Table 4.2.

Table 4.2 Average contrast in properties for the zones included in the Basic model estimated from tomograms.

Property	Background values	Contrast
Seismic velocity (P-wave)	6 300 m/s	3 %
Seismic velocity (S-wave)	3 650 m/s	3 %
Radar velocity	120 m/µs	5 %
Radar attenuation (22 MHz)	28 dB/100 m	80 %
Radar attenuation (60 MHz)	42 dB/100 m	60 %

The velocity contrasts between the fracture zones and the background rock are seen to be quite small, although the contrast in radar velocity is roughly double the contrast in seismic velocities. The contrasts in radar attenuation are significantly larger than the velocity contrasts which makes amplitude tomography a more sensitive method. Similar contrasts in seismic amplitudes are expected but have not been studied within the project.

5 COMPARISON OF THE GEOPHYSICAL MODEL WITH HYDRAULIC DATA

5.1 INTRODUCTION

The geophysical techniques used on the Crosshole Programme were combined to yield the "agreed-on" Basic model of the Crosshole Site. This model is essentially geometrical and as such contains no geophysical appraisal of the hydraulic properties of the identified zones. The zones are identified on the basis of their "contrast", "extensiveness", and their "persistence". The hydraulics data are of a different form since they infer very little (except in special circumstances) of the nature of a "zone" or a fracture away from the immediate vicinity of the borehole.

However, in order to assess the effectiveness of the geophysical techniques in identifying features which are hydraulically important, these two data sets require to be combined or compared.

The first method of comparison is to examine the locations where the identified zones cross the boreholes and assess whether the hydraulic properties in that region are unusual (or of particular significance).

The second method is to examine all data in the same region and assess whether data, of different types, vary in the same way.

A third, less direct method, is to make a conclusion from one method which would have an effect on the other and then check to see if it occurred.

The hydraulic data, against which the geophysical model is being compared, are of two forms: single borehole and crosshole. Both are used in this comparison.

5.2 COMPARISON OF THE GEOMETRICAL MODELS WITH SINGLE BOREHOLE HYDRAULIC DATA

5.2.1 Geometry

The "Basic Model" contains the four zones A, C, K, and L which, with their geophysically determined orientations, should cut the boreholes at 20 points. The "Extended Model" which adds Zones E, F, G, and Unit 1 to the four of the Basic Model should amount to 33 intersections. The thickness of the zones at these intersections is variable depending on the technique used to make the observation. However it does not exceed 15 m and is seldom greater than 5 m.

5.2.2 Hydraulic conductivity "anomalies"

The most basic data set against which to compare the geometrical model is that of transmissivity (i.e. hydraulic conductivity times zone length). The comparison is achieved by plotting the position of transmissivity "anomalies" and the position of zones from the models (see Figure 5.1). The transmissivity anomalies are the fractions of the whole borehole transmissivity which are contributed by each zone (i.e. dimensionless). They are only marked if they comprise more than 2% of the total borehole transmissivity.

The hydraulic data can be seen as consisting of 19 basic anomalies:

Borehole	No of anomalies	No of anomalies A,C,K & L	accountable to E,F & "Unit 1"
F1	4	2	1
F2	3	2	1
F3	3	2	1
F4	3	2	-
F5	4	2	1
F6	2	2	-
TOTALS	19	12	4

It can be seen that the identified zones A, C and L account for most of the observed transmissivity of the boreholes. After these three zones the next most effective in accounting for anomalies of transmissivity is "Unit 1" which is part of the "Extended Model". Unit 1 is unusual in that it lies outside the region investigated by all the geophysical techniques and is identified primarily by core logging. Of the other anomalies the one at

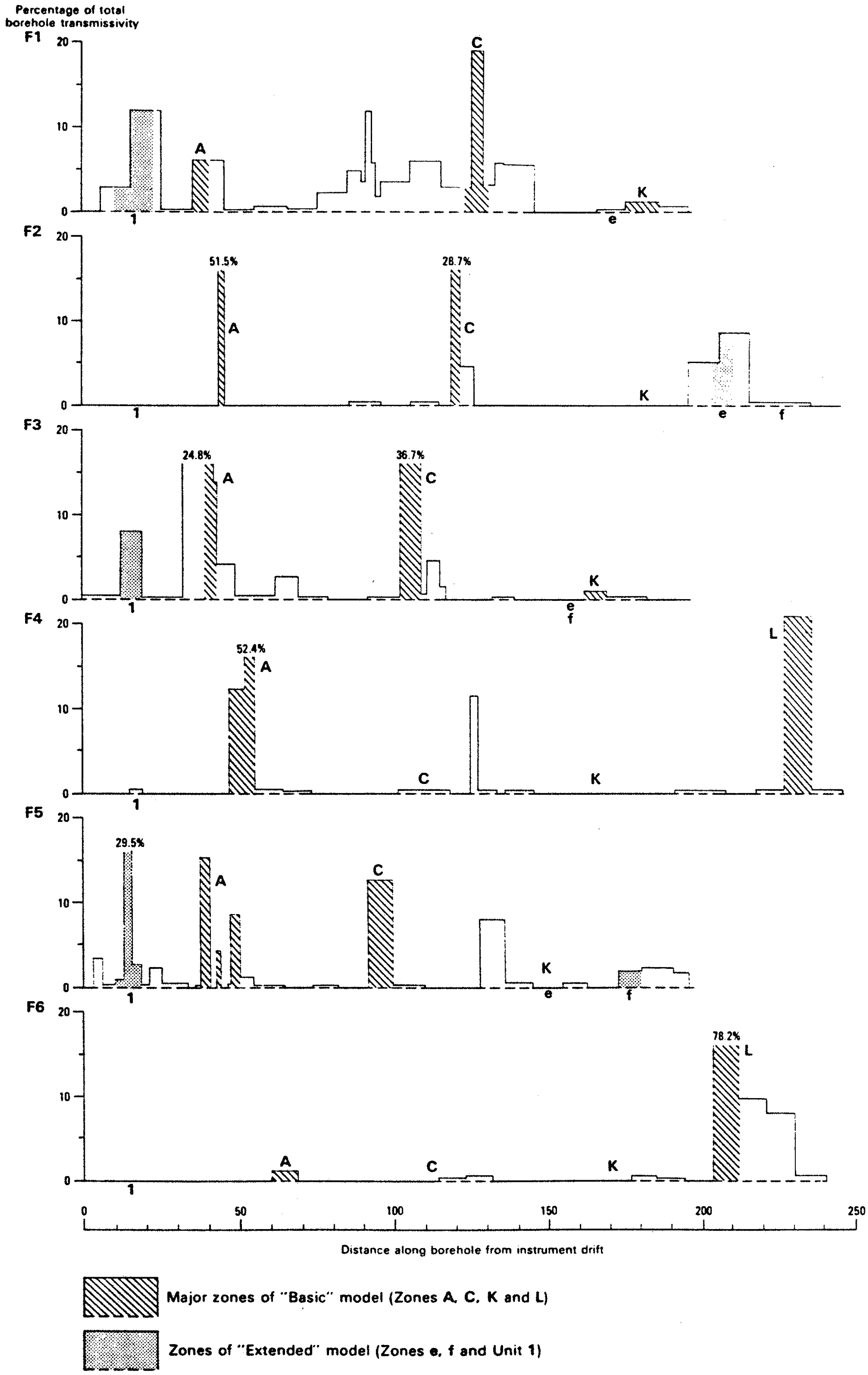


Figure 5.1 The position of transmissivity anomalies compared to the position of major zones in boreholes F1 through F6. (The zones marked in upper case are from the Basic Model, those in lower case from the Extended Model.)

F1:90-96 m is related to the porous granite of small extent named zone B, while for the anomalies at F4:125-127 m and F5:128-136 m there is no association with any identified geophysical anomaly. It may be significant that in all three cases the response of the particular hydraulic test which identified the anomaly indicated a single fracture.

Of the four major zones, Zone A is associated most consistently with high transmissivity. It crosses every borehole within a short distance of a hydraulic anomaly. Zone L is by far the most significant feature seen in the single borehole hydraulic data and is associated with an anomaly at both its expected intersections. At the other end of the spectrum of anomalies associated with zone intersections is Zone K. In all six locations where it should cut the boreholes the hydraulic conductivity is less than a quarter of the average for the individual borehole. It should be borne in mind however that although Zone C seems to disappear at F6 the value of transmissivity where it crosses is at least twice as large as the value where it crosses F1. However it shows as an anomaly in F1 because 8 10^{-9} m^2/s is 27 % of the transmissivity of F1 whereas 2 10^{-8} m^2/s is only 0.7 % of the transmissivity of F6.

This illustrates the difficulty in devising a method of presentation of the results so as to show anomalies in both absolute as well as relative terms. As an example, within the Crosshole Site, F6 penetrates rock which is, on average, 200 times more permeable than the rock penetrated by F1. Within this statistic there is the overwhelming importance of the transmissivity of the 8 metres of rock between 205 m and 213 m in F6 which constitutes 53% of the total transmissivity of the 1300 m of tested boreholes.

5.2.3 Head anomalies

The magnitude of head anomalies is rather more difficult to extract from the testing data than the values of hydraulic conductivity. The head anomalies are extracted from the data in the following way:

1. Assume that the system of groundwater flow towards the old drift and the instrument drift has reached steady state.

2. Calculate the heads that would have been found if the rock behaved as a homogeneous porous medium. This involves iterating within a range of values of presumed homogeneous hydraulic

conductivity. This is to find the value which results in the minimum total difference between the measured and the calculated heads.

3. Note the head difference between the calculated and the measured heads for all the measured zones in the boreholes. These are the "head anomalies".

The head anomalies calculated by the method above are shown in Figure 5.2. Unfortunately boreholes F1 and F2 were measured shortly after the drilling of these holes and before the other holes were drilled. Hence, the first assumption concerning steady state flow was not met. Also the testing method was not very reliable as a method for evaluating "environmental head" relying as it did on short term injections of water at relatively high pressure. These unreliable measurements are coupled with some from later during the programme when all boreholes had been drilled. This leads to a considerable number of spurious "anomalies" as the flow system has not been the same for all tests. Boreholes F1 and F2 have therefore been omitted from Figure 5.2.

The head data can be seen as consisting of 21 basic anomalies:

Borehole	No of anomalies	No of anomalies accountable to A,C,K & L	E,F & "Unit 1"
F3	5	2	1
F4	9	3	1
F5	4	1	2
F6	3	2	-
TOTALS	21	8	4

The largest head anomaly in the Crosshole region is the "old drift" which has a head about 50 m below the instrument drift. It passes through the fan array with a closest approach of about 15 m for the top fan at a distance into the boreholes around 170 m. This then is the region where the largest head anomalies could be expected to be observed. This agrees with the data shown in Figure 5.2. However the head anomalies seen in the boreholes are not nearly as clear-cut as the transmissivity anomalies discussed above. This is a reflection of the fact that hydraulic conductivity varies over 6 orders of magnitude whereas head differences vary between 0 and 70 m. In general an anomaly has been defined as a region of continuous head difference. Where anomalies extend over a considerable length of borehole then an anomaly is ascribed to each peak.

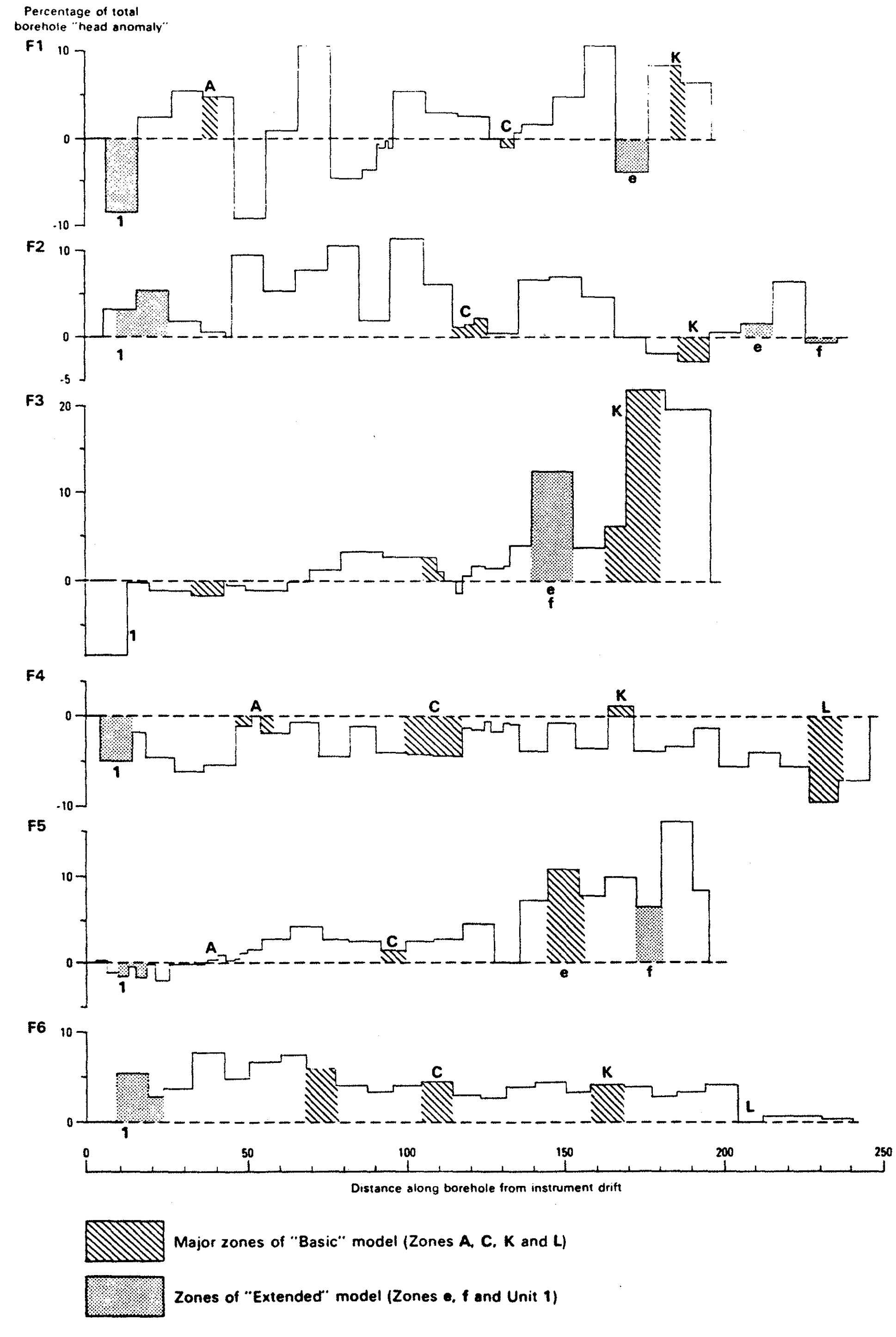


Figure 5.2 The position of head anomalies compared to the position of major zones in boreholes F3 through F6.

This results in F4 in a considerable number of anomalies. A second somewhat arbitrary assumption is the size of anomaly which is ignored. For the purposes of this comparison peak values less than 0.2 m have been ignored.

It can be seen in Figure 5.2 that the zones which account most prominently for the head anomalies are Zone K followed by Zone L. This is in strong contrast to the transmissivity anomalies where Zone K did not show at all.

5.2.4 Flow anomalies

It is possible to construct a third form of anomaly from the single borehole data by multiplying together the previous two. This has the form of transmissivity times head difference which is equivalent to flow. Anomalies defined in this form are measures of the amount of water which would flow into of out of the borehole at a particular location. The results of this combination (see Figure 5.3) can be summarised:

Borehole	No of anomalies	No of anomalies A,C,K & L	accountable to E,F & "Unit 1"
F3	3	3	-
F4	3	2	-
F5	4	2	2
F6	2	2	-
TOTALS	12	9	2

This represents the best percentage accounting for the anomalies by the "Basic" and the "Extended" models. This may be due in part to the exclusion of data from F1 and F2. However if Figure 5.1 and Figure 5.3 are compared it can be seen that the weightings of certain zones are shifted by the inclusion of the head data.

5.2.5 Correlations

It is apparent that there is a correlation between features identified by single borehole hydraulics and single and crosshole geophysics. It is also apparent that whichever way the single borehole hydraulic data are treated, they yield a naturally smaller group of features than the geophysical data. The amount of overlap between the various sets of data are shown in Figure 5.4. This shows that the "Flow" anomalies are a slightly closer subset of the geophysical features than any other. The least

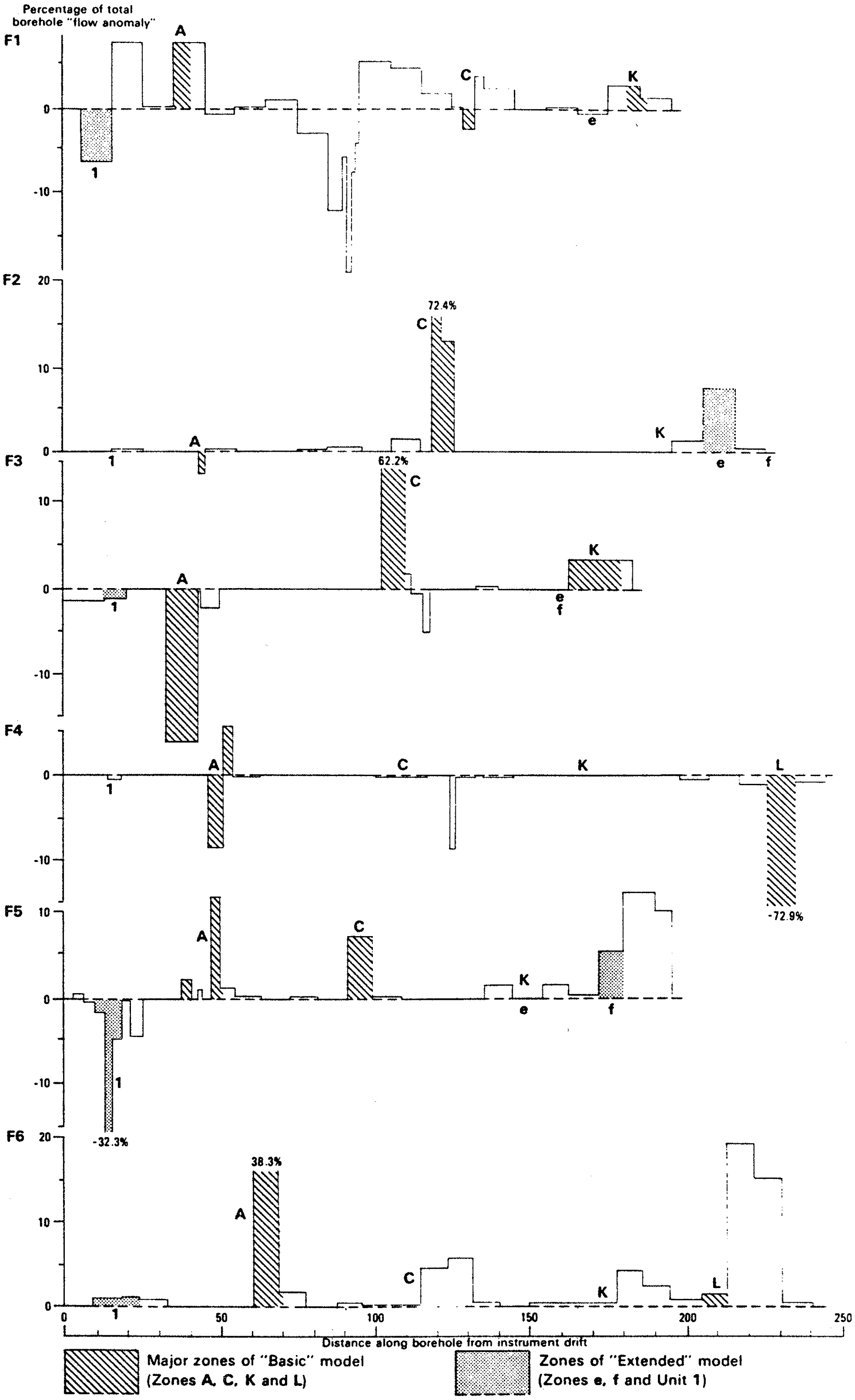


Figure 5.3 The position of "flow" anomalies compared to the position of major zones in boreholes F3 through F6.

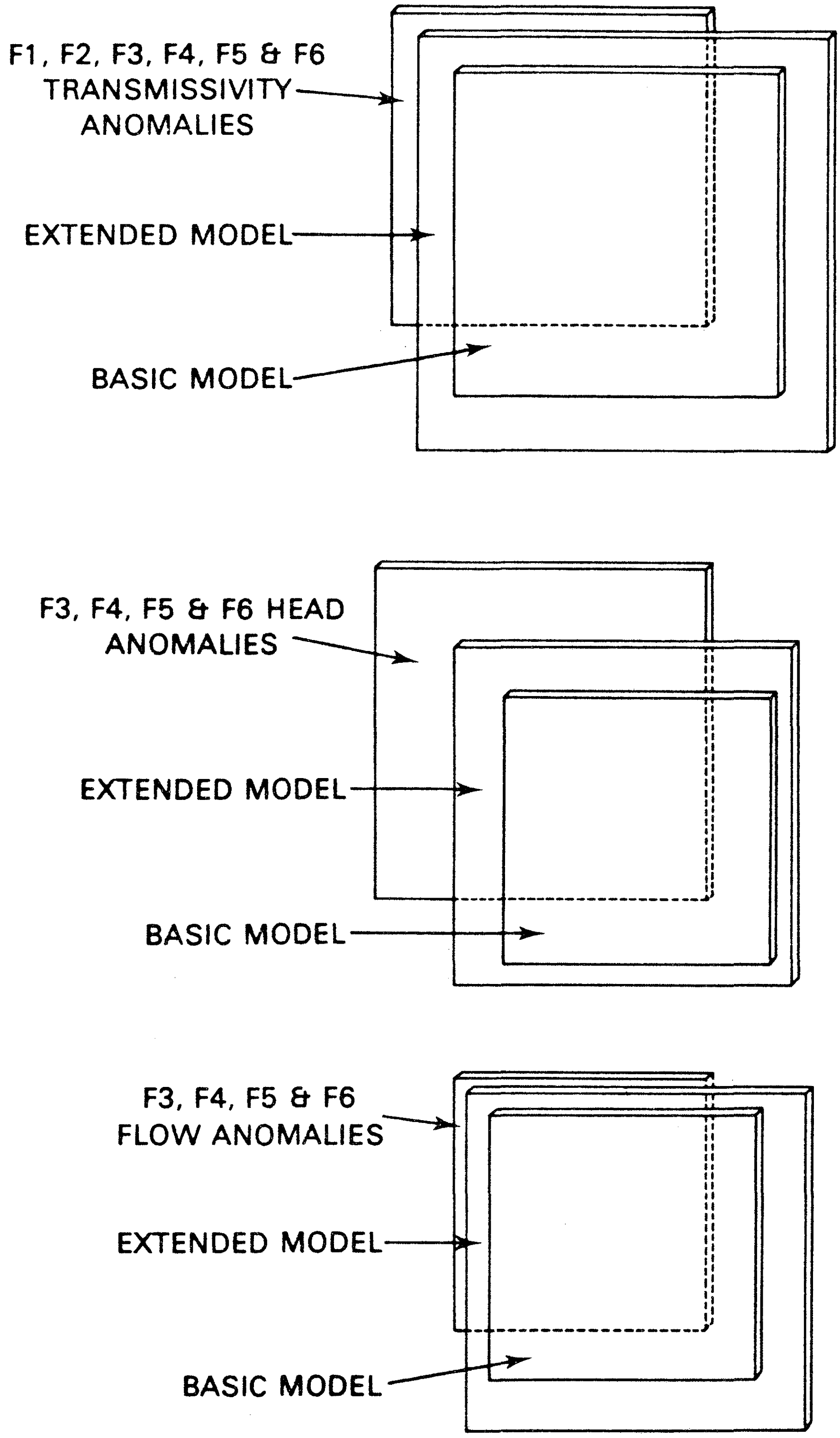


Figure 5.4 The relationship between sets of hydraulic anomalies and the Basic and Extended Models.

effective is the head data, but against that the head data are probably the data set which are most poorly measured.

5.2.6 The nature of the coincidence of hydraulic and geophysical data

The previous sections comparing hydraulic anomalies to fracture zone intersections tend to give the impression of crisply identifiable fractures and rather woolly hydraulic zones. This is not strictly the case and some illustrations are given.

Firstly, the fracture zones are not single fractures but probably zones in which fractures are more frequent than average and more systematically interconnected. When such zones are observed by crosshole geophysics and interpreted by tomographic analysis, they appear less like planes and more like interconnected patches.

The previous section on anomalies showed that some forms of hydraulic anomaly coincide better with the "planar" geophysical model than others. Broadly it was in the order "flow", "transmissivity" and "head". However if the hydraulic anomalies are compared directly to the tomograms then the hierarchy is less clearcut.

Three sets of tomographic cross sections have been chosen to illustrate the comparison. The first set of tomograms (Figure 5.5) shows the cross section between F1 and F6. In this section Zone C cuts through the centre with Zone K on the right hand edge. The profile of transmissivity best-matches the tomogram in the vicinity of F1 whilst that of head probably seems best against F6.

The second section (Figure 5.6) is between F3 and F4 and shows that the profile of head differences most closely matches the tomogram around F4. The flow profile of F3 is probably the other best-match within this section. Zone K passes almost vertically across the centre of the section with an apparent bifurcation in the region of F4. Zone C shows up as a clearly planar zone though its strength varies within the section. The unaccountable aspect of this section is the absence of any hydraulic anomaly associated with the intersection of Zone C with F4. Even head data which should respond to flow anomalies in the near vicinity does not respond convincingly to the proximity of Zone C.

The third section (Figure 5.7) is between F2 and F5. In this section, Zone C is the prominent patch to the left of the centre with Zone K occupying the right hand side of the tomogram. The profile of deduced flow appears to best-match the tomograms in both boreholes. However Zone K does not seem to yield any perceptible anomalies in any of the hydraulic profiles.

Overall it can be seen that there is no one form of viewing the hydraulic data so as to get direct agreement with the geophysical results.

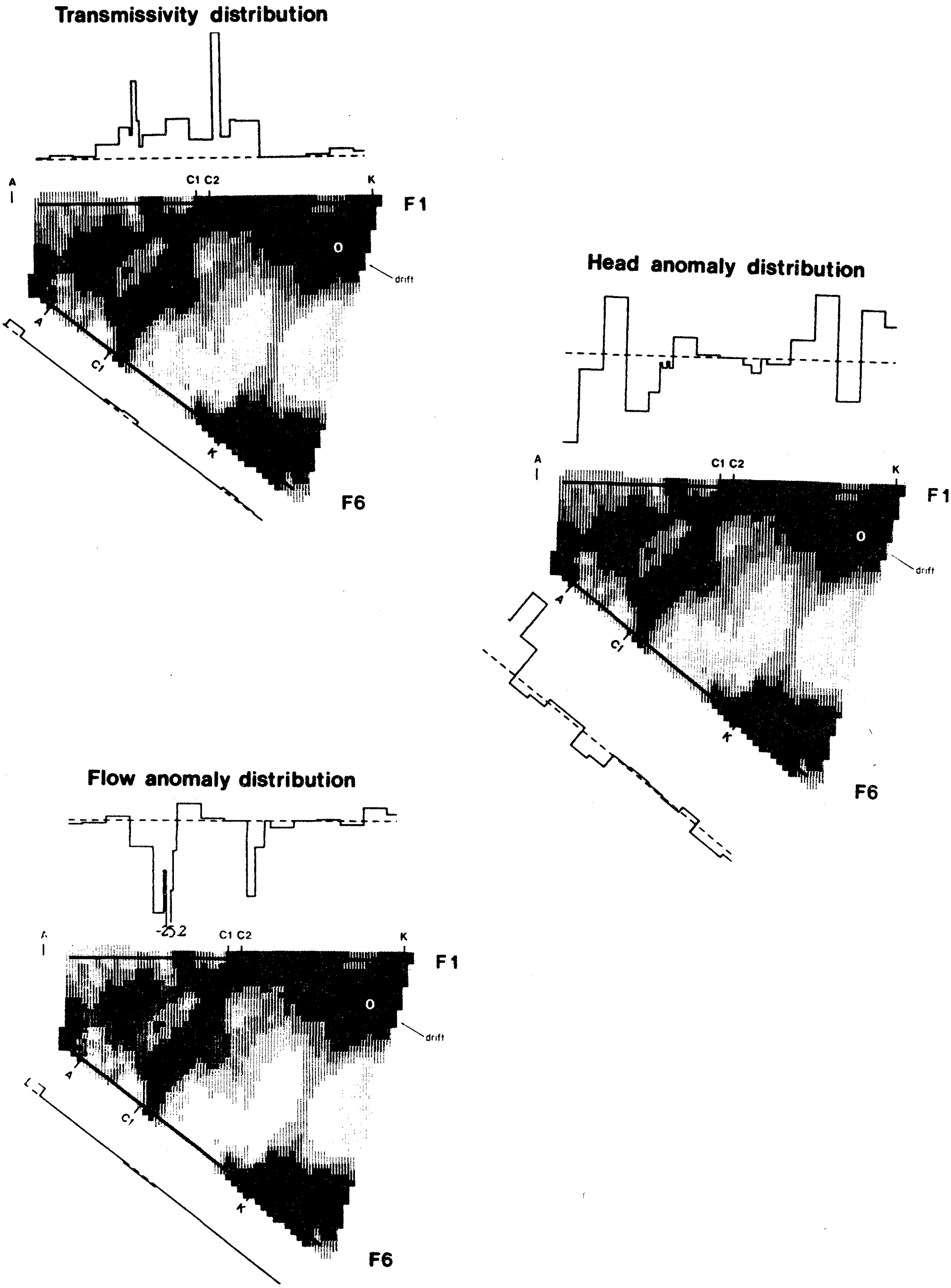


Figure 5.5 The comparison between the radar tomogram for section F1-F6 and hydraulic anomalies along these boreholes.

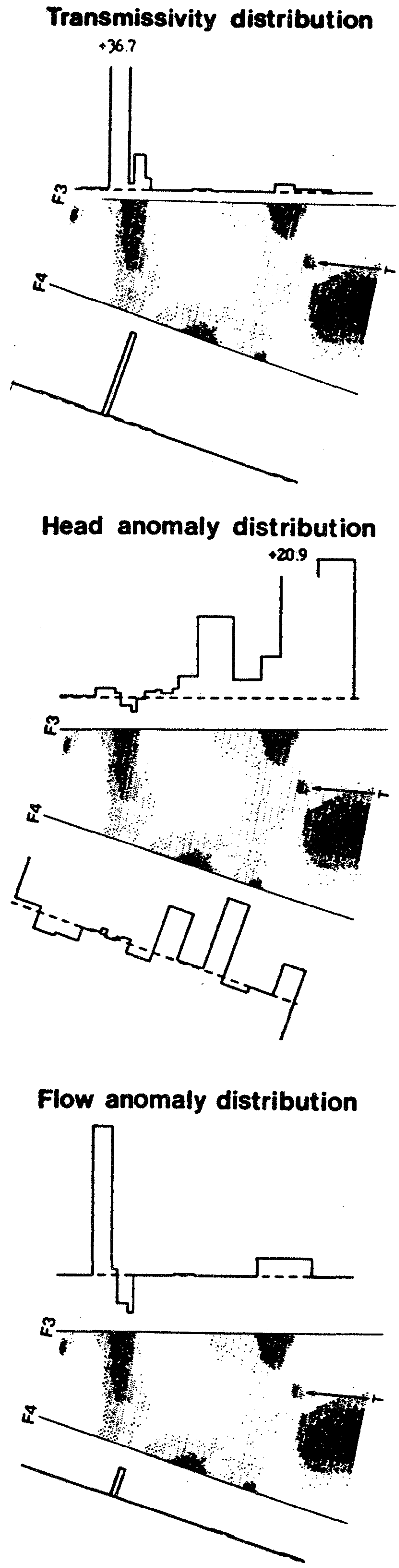


Figure 5.6 The comparison between the seismic tomogram for section F3-F4 and hydraulic anomalies along these boreholes.

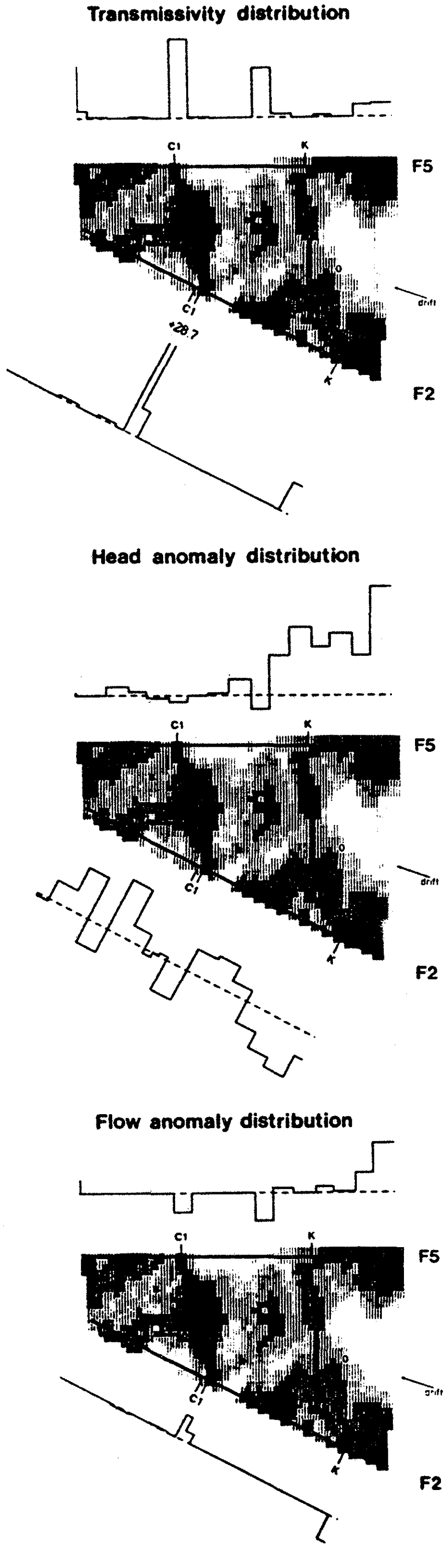


Figure 5.7 The comparison between the radar tomogram for section F2-F5 and hydraulic anomalies along these boreholes.

5.3 THE HYDROGEOLOGY OF THE FRACTURE ZONES OF THE BASIC MODEL

The crosshole hydraulics which have been carried out have only effectively investigated Zones A and C. However by combining some of the single borehole measurements, conclusions can be drawn concerning the characteristics of the two other zones of the Basic Model (K and L).

5.3.1 Zone A

Of all the zones, Zone A was the most extensively tested using the crosshole sinusoidal technique. It was measured as being well interconnected in the centre of the fan-array system of boreholes. Although it did not respond at all in F1, in the nearby F3 it responded in 4 separate receiver zones spanning 13 m (Figure 3.4.4). Coming further south to F5 there were again 4 responding 2.4 m long zones but in this borehole there was an intervening non-responding receiver zone. Hence the Fracture Zone A appears to bifurcate and grow wider across the "fan-array". In the lowermost fan of boreholes (F2, F4, and F6), F2 in the north has one responding receiver zone, F4 has three whilst F6 was not investigated. This again indicates an increase in width of the zone in the southerly direction.

The properties deduced from these crosshole measurements were based on analysis using fractional dimensions. There are two basic hydraulic results: firstly the dimension of the flow decreases towards the north (i.e. towards F1 and F2) and secondly the hydraulic diffusivity (K/S_s) appears to increase towards the north (Figure 3.4.5). The first result would be in line with the appearance that Zone A splits up into a number of adjacent conductive fractures (or a denser network of channels) in the south of the Crosshole site. However, in order that an increased number of channels or fractures should be associated with a decrease in hydraulic diffusivity, the amount of "flow porosity" cannot increase. This can be envisaged as the example where one fracture of 10 mm aperture splits into 5 fractures each with an aperture of 2 mm. In this example the total hydraulic storage of the system would remain constant but the transmissivity would decrease resulting in an overall decrease in hydraulic diffusivity. This interpretation is borne out by the single borehole data which yields approximate transmissivities for the regions where Zone A is expected as follows:

borehole	transmissivity (m^2/s)	length of zone(s) (m)
F1	$2\ 10^{-9}$	10 (1)
F2	$3\ 10^{-7}$	2 (1)
F3	$5\ 10^{-7}$	11 (1)
F4	$4\ 10^{-7}$	8 (1)
F5	$1\ 10^{-7}$	6 (3)
F6	$5\ 10^{-8}$	8 (1)

This shows basic agreement between the single borehole and the crosshole hydraulics. It appears that Zone A branches into more numerous but, in total, less transmissive fractures in the south of the site. This branching is seen as an increase in the fractional dimension of the crosshole sinusoidal analysis. In the north of the site (around F1 and F2) the zone becomes a single fracture. In F2 it produced a remarkable cross-borehole response to a slug test in F4 which is about 15 m distant. This indicates a low-storage, high-conductivity connection between the two boreholes.

5.3.2 Zone C

The crosshole testing of Zone C yielded a similar picture of multiple zones and decreasing hydraulic diffusivity. This time however the orientation was reversed and the bifurcations increased to the north. Similar to Zone A, it was not seen to connect into F1 so that despite some considerable testing effort in that borehole no responses were seen. Perhaps strangely, there were 5 responding zones in F2 only 20 m away spread over 20 m of the borehole length. The next pair of boreholes to the south (F3 and F4) gave 4 responding intervals spread over 13 m in F3 and one 4 m long interval in F4. There was only one responding interval in borehole F5. Hence we see a zone which apparently bifurcates towards the north. The fractional dimensional analysis of the sinusoidal tests found a similar indication to Zone A except that in Zone C the apparent dimension of the 24 hour period tests increased towards F2 (i.e. towards the north and in the direction of increasing number of responding intervals). Again, similar to Zone A this increasing dimension was accompanied by decreasing hydraulic diffusivity. It decreased from 1 m^2/s between F3 and F5 to 0.3 m^2/s between F3 and F2. These results were obtained over larger distances than in Zone A and were accompanied by smaller fractional dimensions. In both the analyzable cases these fractional dimensions were less than 2 indicating a less than planar feature: a network of channels. This crosshole based interpretation is complicated by considering the single borehole data which yields approximate transmissivities for the regions where Zone C is expected as follows:

borehole	transmissivity (m^2/s)	length of zone (no.) (m)
F1	$6\ 10^{-9}$	4 (1)
F2	$2\ 10^{-7}$	7 (2)
F3	$5\ 10^{-7}$	7 (2)
F4	-	-
F5	$5\ 10^{-8}$	8 (1)
F6	$5\ 10^{-8}$	17 (2)

This shows basic agreement between the single borehole and the crosshole hydraulics in as far as F4 did not yield any crosshole responses and appears to have no localised enhanced transmissivity. It appears from the single borehole data that Zone C is most permeable in the centre of the site. Perhaps the consistent explanation of the data lies in seeing Zone C as a highly channelised zone.

5.3.3 Zones K and L

These zones were not tested specifically by the crosshole method but some general testing was performed in order to determine whether it would be worthwhile to search for crosshole connections. Hence a constant rate test carried out in the bottom of F6 (i.e. Zone L) was not seen as a positive crosshole test in any other borehole. However some conclusions can be drawn from this "non-result" when combined with the single borehole results. Firstly Zone K does not show as a zone of enhanced transmissivity in any of the boreholes except F3 where it attains a value of $1\ 10^{-8}\ m^2/s$ over a 7 m length of borehole. Compared to the values for the other zones this is not a particularly high value and it would be difficult to obtain a crosshole response within a zone of this magnitude over any significant distance.

The highly transmissive Zone L was tested using a constant rate type test but a signal was not seen in borehole F4 where it could have been expected because the pressure disturbance created in F6 was comparatively small. In addition it was difficult to determine the response to such a test against the changing background at the time of the test. However the single borehole results show a 26 m wide zone in F6 with a transmissivity of $4\ 10^{-6}\ m^2/s$ and a 9 m zone in F4 with a value of $1\ 10^{-7}\ m^2/s$. Again it is clear that the thickness of these zones varies considerably within the scale of the Crosshole Site.

5.3.4 Average rock

Between the major features occurs fractured rock which has no special properties. Clearly it is not simply matrix rock with the appropriate hydraulic properties of about $1x10^{-12}$ m/s for K and $1x10^{-6}$ 1/m for S_s. The properties of the intervening rock can be derived by taking the overall properties of the site and subtracting the properties of the major features. This yields an average K for the intervening rock of about $2x10^{-10}$ m/s. In other words, borehole F1 penetrates "average rock". In contrast, the average K of the fracture zones is about $5x10^{-8}$ m/s.

5.4 COMPARISON OF RADAR FEATURES WITH SINGLE BOREHOLE HYDRAULIC CONDUCTIVITY RESULTS

5.4.1 Introduction

A simple analysis procedure has been developed to allow a comparison to be made between the features detected by radar and single borehole hydraulic testing results. In general terms, certain zones with higher values of hydraulic conductivity are defined in each borehole. The position of each radar feature is compared to the nearest zone by distance. If a feature occurs within a zone then the distance score is zero. However, if a feature falls outside a zone the distance to the nearest zone is calculated and termed the "miss distance". The miss distances for all the radar features are summed divided by the number of features and an "average miss distance" (a.m.d.) is calculated. A distribution of notional amd's is derived by repeatedly placing (200 times) the same number of features randomly along the borehole. This distribution is characterized by a mean amd and arranged so that the amd's smaller than the mean have a chance of occurring between 0 % and 50 %. The value of the actual amd lies within this distribution and indicates, when having a value of less than 50 %, if the actual features correlate with the zones of high hydraulic conductivity and can, therefore, predict water flow in the fractured rock mass.

The comparison has been attempted with two separate groups of radar features. Firstly, a set of unweighted features determined soon after the collection of field data. Secondly, a set of features resulting from a more detailed consideration of the original data in which the likely significance of each feature has been assigned a weighted value.

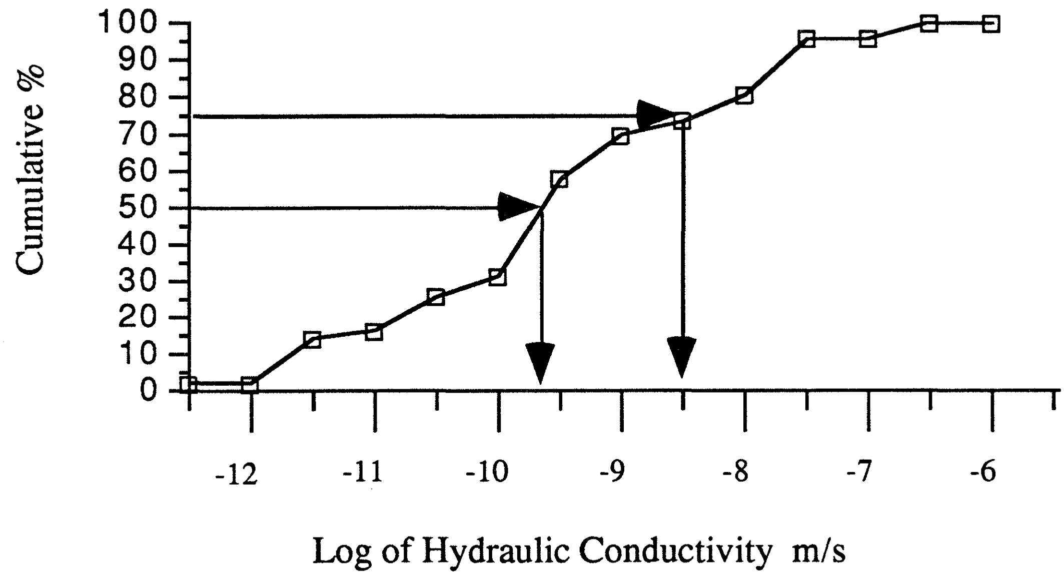


Figure 5.8 Cumulative frequency distribution plot for F3.

5.4.2 Procedure

Zones of high hydraulic conductivity are determined from cumulative frequency distributions of the single borehole test results based on occurrence, per metre, of values of the logarithm of hydraulic conductivity. Figure 5.8 presents such a distribution for borehole F3. For the comparison method, zones were defined based on 50 % and 75 % levels of the distribution. Each level produces a value of hydraulic conductivity.

In Figure 5.9, the values of hydraulic conductivity at the 50 % and 75 % levels are plotted on the log of single borehole results. Those zones which are located above the percentage lines were selected for inclusion in the comparison test.

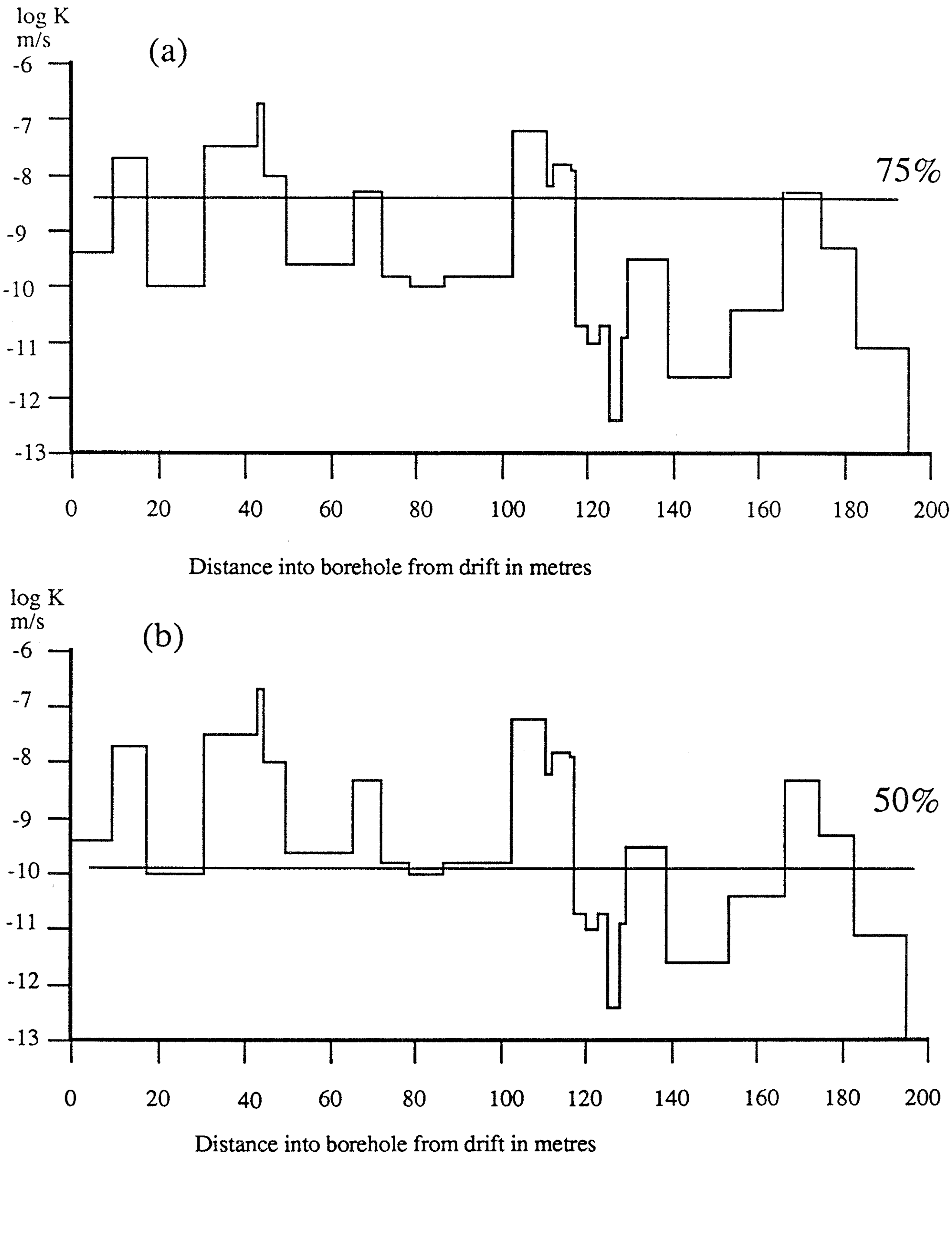


Figure 5.9 Selection of zones from hydraulic single hole tests.

The comparison between the radar features and the zones of high hydraulic conductivity is performed by a computer. The zones are entered as start and end distances, measured from the drift. Radar features are entered as single distances. The programme examines each of the radar features in turn and relates its position to the nearest zone. If the feature falls within a zone, it is allocated a score of zero. If it falls outside the nearest zone,it is assigned a distance score from the nearest edge of the zone. When all the features have been examined the distance scores are added together and divided by the total number of features to provide an average missing distance score. The program also calculates average missing distances for a series of randomly generated features. A reseeded random number generator locates an identical number of features along the length of the borehole. These are run through the programme to produce an average missing distance score. Two hundred sets of features are generated and the results are plotted on a frequency diagram. The missing distance score of the real radar features can be plotted on the same diagram. Figures 5.10 and 5.11 show such a plot for F3 and F5 for the 75 % zone selection and the preliminary set of unweighted radar features. The percentage of the random missing distance distribution which is lower than the real distance can be used as a measure of comparison. For borehole F3, 18 % of the random distribution has an amd less than that measured indicating that the actual radar features correlate closely with zones of high hydraulic conductivity. However, in borehole F5 a value of 73 % is calculated indicating randomly distributed features would usually be closer to zones of high water flow than the specifically identified radar features.

The radar features have been selected in two ways. In the first set no weighting has been applied to the features so that each is considered to have a similar potential for water flow. In the second set a weighting has been applied to the features using the following criteria (Appendix B in Olsson, Falk, Forslund, Lundmark, and Sandberg, 1987);

1) very strong and persistent reflections corresponding to major fracture zones,

2) a strong and clear reflection often visible at large range from the borehole,

3) a weak but well-defined reflection,

4) barely visible reflection.

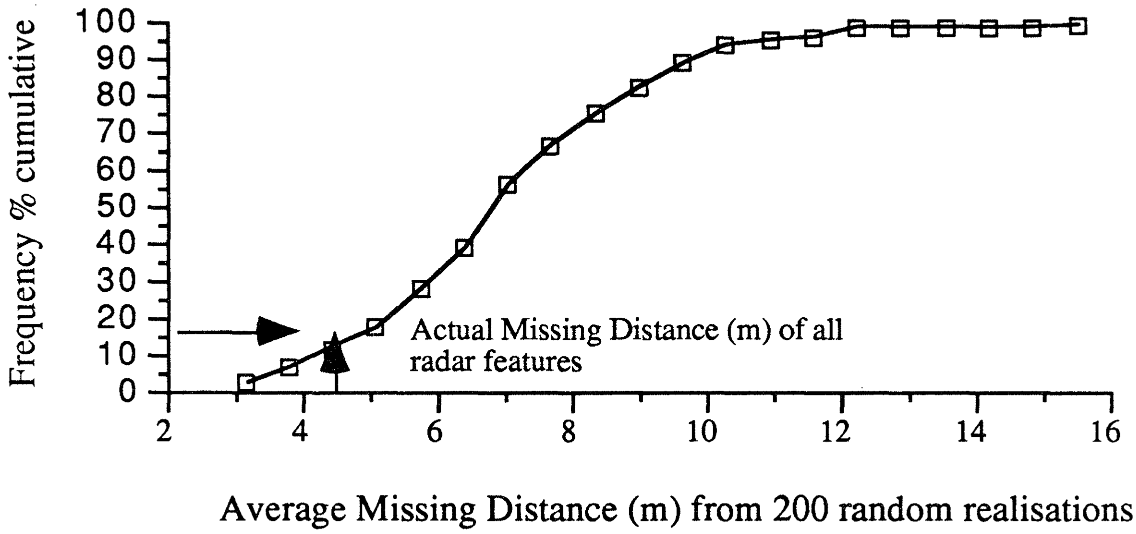


Figure 5.10 Borehole F3 - Plot of percentage distribution.

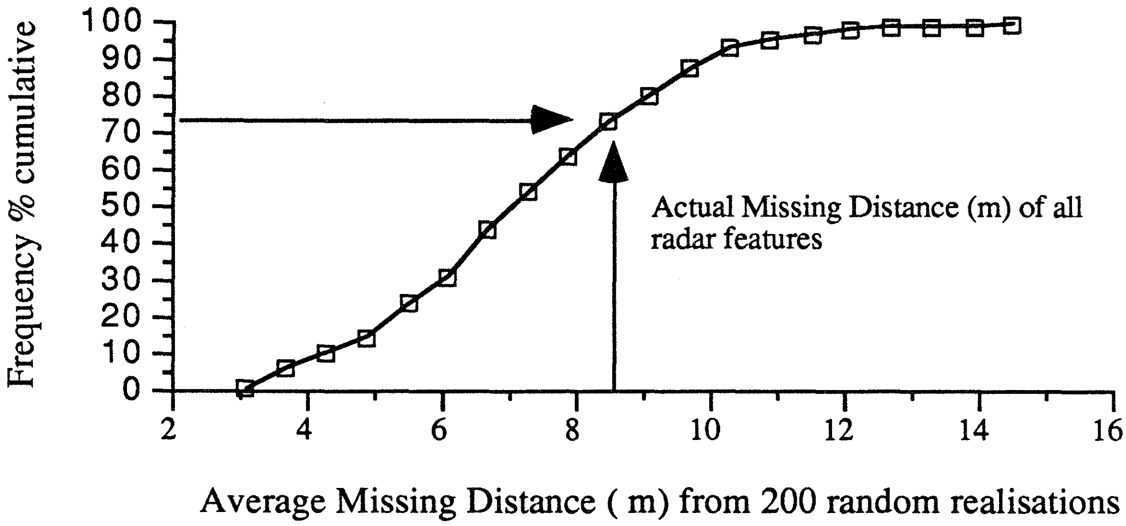


Figure 5.11 Borehole F5 - Plot of percentage distribution.

Additionally radar features detected by using two frequencies of signal, 22 and 60 MHz, are included in the analysis. The lower frequency signal should penetrate further into the rock but has less definition than the higher frequency signal.

5.4.3 Results

Table 5.1 lists the results of the analysis for each borehole in the test array at the 50 % and 75 % levels of hydraulic results and the unweigthed radar features. For each test the average missing distance (amd) of the actual data is presented together with the mean amd of the distribution of random features.

Table 5.2 lists the analysis results of the weighted radar features against zones of hydraulic conductivity which are significant at the 75 % level. Results at both the 22 and 60 MHz frequencies are shown. The feature level indicates the type of radar feature included in the analysis. Level 1 only includes the very strong and persistent features whilst 1+2+3+4 includes everything. A graphical representation of the data set is given in Figure 5.12.

Test Number	Actual Average Missing Distance (AMD in M.)	Average AMD of 200 random realisations	Distribution of random results with lower AMD than actual
F1 50%	8.08	9.33	41.0
F1 75%	14.31	13.41	59.5
F2 50%	2.47	3.63	22.0
F2 75%	9.27	11.19	27.5
F3 50%	1.67	3.10	13.5
F3 75%	4.50	6.97	18.0
F4 50%	3.14	3.86	34.5
F4 75%	15.92	13.08	77.0
F5 50%	3.41	3.56	48.5
F5 75%	8.50	7.11	73.5
F6 50%	4.59	4.52	55.0
F6 75%	11.71	12.67	40.5

Table 5.1 List of missing distance scores for unweighted radar features.

Borehole and Signal Freqency	Feature Level	Actual Average Missing Distance (AMD in M.)	Average AMD of 200 random realisations	Percentage of random results with lower AMD than actual
F1 22 MHZ	1	2	14.35	6.0
	1+2	1	12.10	5.0
	1+2+3	6	13.49	15.0
	1+2+3+4	7	13.27	15.0
F1 60 MHZ	1	2	14.35	6.0
	1+2	1.33	13.45	5.0
	1+2+3	17.28	13.06	78.0
	1+2+3+4	16.8	13.98	73.0
F2 22 MHZ	1	0	10.89	0.0
	1+2	2.6	10.88	3.5
	1+2+3	2.25	10.98	1.5
	1+2+3+4	5.67	11.07	8.0
F2 60 MHZ	1	0	11.88	0.0
	1+2	7.57	10.99	24.0
	1+2+3	7.73	10.82	24.0
	1+2+3+4	8.25	11.36	20.5
F3 22 MHZ	1	0	6.54	0.0
	1+2	3	7.31	10.0
	1+2+3	5.37	7.13	25.5
	1+2+3+4	6.2	7.08	37.0
F3 60 MHZ	1	0	6.91	0.0
	1+2	2.2	7.42	5.0
	1+2+3	2.86	7.19	5.5
	1+2+3+4	2.5	7.08	3.5
F4 22 MHZ	1	8	12.55	40.0
	1+2	15.37	12.23	77.5
	1+2+3	12.38	12.28	54.0
	1+2+3+4	12.07	12.46	48.0
F4 60 MHZ	1	18	12.21	94.5
	1+2	16.67	12.81	84.0
	1+2+3	16.38	12.04	87.0
	1+2+3+4	16.38	12.04	87.0
F5 22 MHZ	1	0	6.30	0.0
	1+2	6.33	7.44	43.5
	1+2+3	13.55	6.93	97.0
	1+2+3+4	12.36	6.80	99.0
F5 60 MHZ	1	1	7.45	10.0
	1+2	8	6.66	77.0
	1+2+3	7.13	6.91	57.0
	1+2+3+4	7.13	6.91	57.0
F6 22 MHZ	1	8.5	13.16	44.0
	1+2	10.75	12.87	40.5
	1+2+3	9.56	12.58	29.0
	1+2+3+4	10.2	12.80	31.5
F6 60 MHZ	1	15	11.12	70.5
	1+2	5.33	12.45	12.5
	1+2+3	7	12.97	8.0
	1+2+3+4	7	12.97	8.0

Table 5.2 Missing distance scores for weighted radar features.

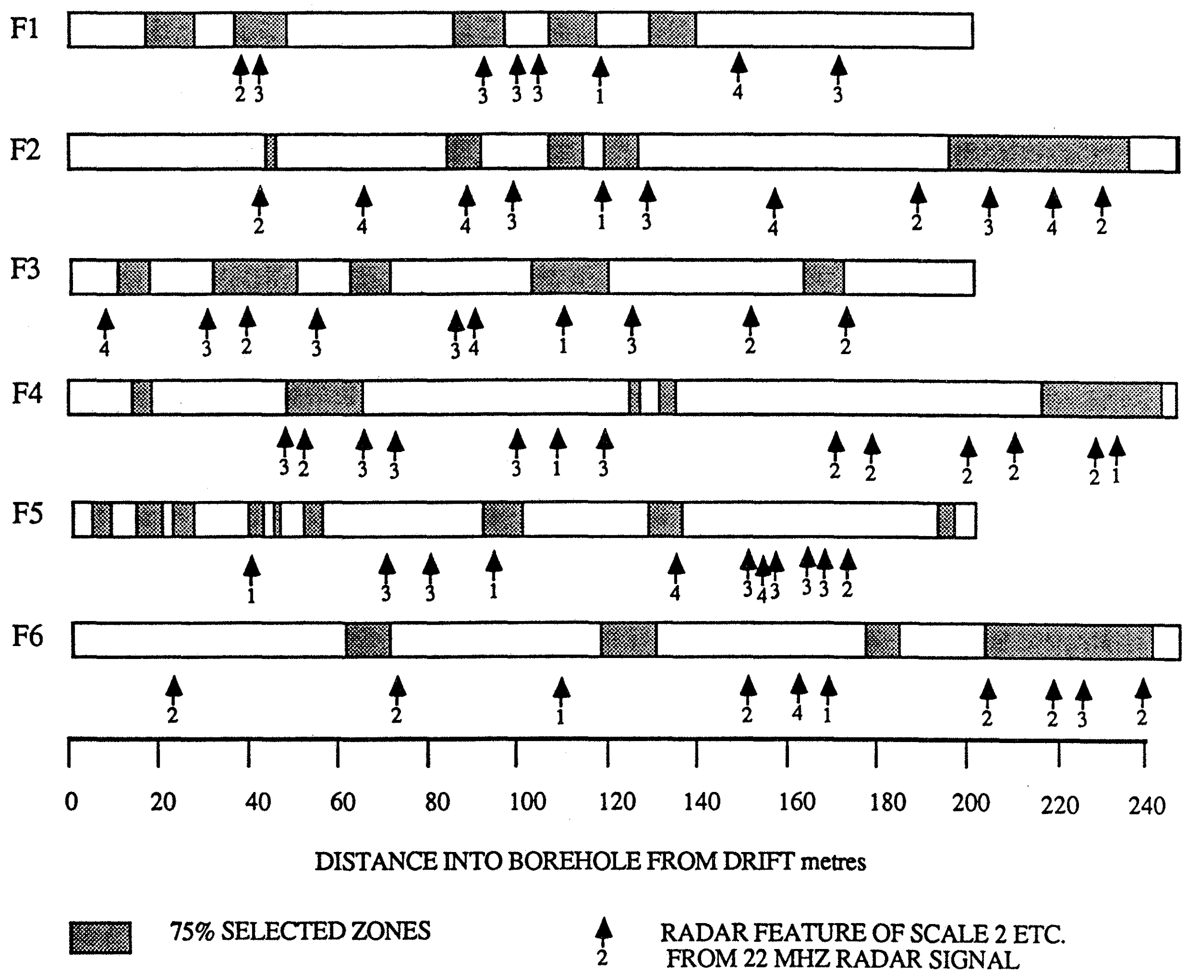


Figure 5.12 Position of weighted radar features and hydraulically conductive target zones at the 75 % level.

5.4.4 Discussion

The results of the analysis using the unweighted features indicates that radar successfully identifies hydraulically significant features in only two of the six boreholes, i.e. F2 and F3. This means that in the other boreholes a random distribution of features was closer to the hydraulic features than radar identified zones. However, the values in these 4 other boreholes was quite close to the mean random distance. As would be expected the missing distance increases between the 50 and 75 % level reflecting the decrease in potential target zones.

In general, the weighted radar features show a better correlation. At feature levels 1 and 2 there is generally a very good correlation between radar features and zones of high hydraulic conductivity except for boreholes F4 and F6. If features of level 3 and 4 are included the missing distance of the radar features becomes comparable to the random distributions. If the smaller radar features are included the number of radar features increases significantly and becomes substantially larger than the number of hydraulic features. Considering that the smaller radar features represent minor geological features which are not likely to be of hydrogeologic significance a deterioration in correlation between the two data sets is to be expected.

5.4.5 Conclusions

In general the single borehole reflection radar identifies more features of interest than the single borehole hydraulic testing. To some extent this is probably a result of the relatively coarse packer spacing (i.e. 4-13 m with overlaps) as much as it is a real feature of the rock and fractures. If the number of radar features are reduced by a weighting procedure the there is a good correlation between radar identified features and hydraulically conductive zones. The poor correlation of unweighted data suggest that many of the features seen by single borehole radar are hydraulically insignificant. This may well be a function of their extent and the nature of radar interpretation in the single borehole reflection mode.

6 DISCUSSION

6.1 ASPECTS OF SITE CHARACTERIZATION TECHNIQUES

6.1.1 Use to construct models

The ultimate aim of a site characterization of a waste repository site is to predict the likely speed and direction of migration of leached radionuclides through the site. This requires a model of the spatial distribution of relevant properties. At its simplest, the model would be a volume of homogeneous material. At its most complex, the model would include every detail concerning the minerals and the water-filled voids within the volume of rock investigated. In actual site investigations the complexity of the model reflects, amongst other considerations, particular aspects of the techniques used.

The investigation of the Crosshole site concerned an evaluation of the techniques which would be used to construct a model of the flow of water (a less complex model which underlies a nuclide transport model). The techniques tend to supply information either, concerning the geological structure (i.e. the arrangement of fault zones, etc.) or relevant properties within predetermined features (i.e. the hydraulic conductivity of intercepted fractures). There is some overlap between the techniques. For instance, radar techniques indicate not just the position and orientation of fractures but also yield data on the local relative electrical resistance. Conversely hydraulic techniques yield measurements of the properties of a region together with limited information on the geometrical arrangement of those properties.

In comparing the results from the various techniques, these aspects need to be borne in mind together with considerations on the "natural dimension" of the measurement and its characteristic scale.

Table 6.1 The effective "dimension" of the site characterization techniques used.

Measurement	primary result	secondary result	dimension of measurement
core logging	geometry	(properties)	1D (minor 3D)
core measurements	properties (of rock matrix)		1D
single borehole geophysical logging	properties	(geometry)	1D
single borehole hydraulics	properties	(geometry)	1D (minor 3D)
single borehole radar	geometry	properties	pseudo 3D
crosshole* radar and seismics	geometry	properties	2D-3D*
crosshole hydraulics	properties	geometry	pseudo 3D

* a form of 3D can be obtained by combining 2D sections

6.1.2 Natural dimension of measurements

Even though all the measurements were made in the boreholes of the Crosshole Site, the arrangement of source and receiver naturally imparted a "dimension" on the derived results. In some cases the measurement responded to a small region around a line or plane of measurement which was usually small compared to the scale of the total volume to be investigated. In other cases a measurement implies some particular three-dimensional arrangement of properties but does not uniquely specify their position or size. This is termed here as "pseudo-3D". The investigation techniques are listed by their "natural dimension" and their effective results (property or geometry) in Table 6.1.

It can be seen in Table 6.1 that amongst the "normal" single borehole techniques (the first 4 items in the table) there is considerable scope for intercomparison. However none of them provide any large scale geometrical information and they have already been systematically compared in other studies (e.g. Magnusson and Duran, 1984). The need to derive the distribution of properties within a comparatively large region (volumes with sides of at least 100 m) lies at the centre of the Project so it is intercomparison of the second four techniques in the list which is of major concern in this study. In general, the model of a site is based on those techniques whose primary result is geometry and have a reasonable scale and aspects of three dimensions. As can be seen from the table the crosshole radar and seismic techniques have these characteristics but differ from hydraulic measurements to which they need to be compared.

6.1.3 Scales of observation

In general, the "scale" of a measurement method has two aspects: minimum resolution size and normal sample size. To a large extent these two aspects are related.

The techniques used in the Project contain a wide range of minimum resolutions. At the smallest scale the core logging resolves features down to fractions of a millimetre, whilst at the other end of the spectrum, crosshole seismics and radar resolve on the order of half a wavelength (i.e. a few metres). In practice, a positive identification of a fracture normally requires it to have at least one dimension which is several times the minimum resolution, i.e. about 10 m or more. However, the crosshole geophysical methods determine the broad geometry of the model and hence the effective size of potential features. The question of minimum resolution also affects the presentation of results. To facilitate comparison of results with different minimum resolution, results of high resolution techniques are averaged and presented with comparable resolution to other methods. For example, fracture frequency data derived from core logging are averaged to one meter intervals.

For measurements which primarily yield results concerning properties rather than geometry, the minimum resolution is effectively determined by the maximum dimension for the region sampled. In cases where the sample region is subdivided the resolution may be improved but usually homogeneity is assumed within a simple cylindrical geometry and the maximum dimension determines the minimum resolution. This is the case for all hydraulic techniques. In most of the single hole testing the region around the borehole which affected the result did not exceed a fraction of a metre. Hence the minimum resolution of the single borehole hydraulics was determined by the minimum straddle interval of 2 meters. The data are effectively one dimensional samples. The maximum dimension of the crosshole testing is the distance between source and receiver points which would result in extremely poor spatial resolution. However, the interpretation of the crosshole hydraulics data is influenced by geometry based on geophysics. Hence the resolution of the crosshole hydraulics is, in reality, a function of the complexity of the geometric model applied in the interpretation. It should be borne in mind that the geometry of the assumed flow paths strongly affects the derived properties.

The techniques which define geometry also have a maximum size of sample which is dependent on the range of propagation of the signal. This is related to signal frequency and hence also to minimum resolution. In the study reported here the maximum sample size used was in the order of two hundred metres (essentially determined by the length of the boreholes). Although the seismic method could have attained larger sample sizes (as at Gideå), no other method could have been compared.

6.1.4 Resulting model

The model of the Crosshole site presented in the previous chapters has been made with the restrictions in scale described above. Hence, no feature included in the model can be smaller than a few meters. Another consequence is that the separation between identifiable features can not be smaller than the smallest detectable size. If the separation is smaller then the two features would be perceived as a single feature. The model of the Crosshole site contains features with sizes on the order of a few meters, that is close to the detection limit, while the average separation of the identified zones is roughly 70 m for the two different sets. The separation of zones is thus much larger than the resolution and we can expect the model to be correct in that it describes a piece of rock intersected by a number of zones which occupy a minor part of the volume.

The model as such is a rationalization of the data obtained with the different methods. The model is also the result of a qualitative weighting of the information obtained through the different techniques. This weighting has not always been easy to perform as the data have different scales, different resolutions, and yield different physical properties.

An important underlying concept in the construction of the model has been the extensiveness of the features. If we consider water flow from a repository to the surface the transport paths are of considerable length. A basic concept is then the notion that features of large extent are likely to be more significant transport paths than features of limited extent.

6.2 DESCRIPTION OF ZONES

During the initial characterization of the Crosshole site with the "conventional" single-hole methods certain assumptions were made concerning the characteristics of the rock. It was assumed that the rock was intersected by laterally extensive fracture zones which could be identified based on their geological appearance. Brecciation, mylonitization and red coloring are signs of faulting and hence also of lateral extent. These original assumptions have been confirmed by the application of the novel investigation methods. The assumed extension of the fracture zones have actually been verified by the radar and seismic methods which have provided data on the extent of the fracture zones. It is important to note the difference between an extent inferred from borehole observations like core logging and actual data on extent as is obtained by the remote sensing techniques.

The zones of the "Basic" and "Extended" models have been identified on the basis of their "extensiveness" and "strength" as seen by geophysical methods. It is clear from the comparisons with the hydraulic results that, in general, this approach works and that features which are "extensive" are usually "strong" geophysically and are also important hydrogeological features. However, the features are not all the same and they seem to have some geophysical characteristics which are associated with variable hydraulic characteristics. For instance it is clear that Zones A, C and L of the "Basic model" are all more-or-less continuous zones of enhanced hydraulic conductivity. However Zone K of the "Basic Model" is seen by the geophysical methods as a system of patches. For instance the radar reflection data from borehole F4 show a planar feature whose strength of reflection obviously varies. The other zones (A, C and L) are not seen to vary in this way.

The hydraulic data indicate that Zones A and C bifurcate. This can be seen in the tomographic as well as the reflection data. Zone A particularly is seen to bifurcate in the vicinity of F6 and this is where the hydraulic data predict. Additionally where

Zone A is not seen hydraulically in F1 it is also seen by the 60 MHz radar data to stop short of penetrating the borehole.

With these sort of observations it is obviously possible to form a more complete picture than has been possible before. The main features of the "Basic" and "Extended" models are all thought to have the following characteristics:

1. broadly planar
2. channelled
3. a branching, interconnecting network
4. patches of high and low hydraulic conductivity
5. decreasing transmissivity associated with bifurcations

This last characteristic is, in some ways, the most interesting aspect since it is not what might be expected. It possibly results from a fracture system where fractures bifurcate at their extremities in a pattern similar to "en-echelon" faulting.

It would be easy to over-emphasize the planar nature of these features which are essentially networks of channels arranged within a broad region (up to 20 m width) which is larger than it is thick.

A less debatable aspect of the features seen at Stripa are the relative orientations of the features to each other. Zones C, K and L all belong to one set of fractures whilst A belongs to a complementary set. The minimum included angle of about 50° agrees well with theory relating to fault sets.

The other zones of the "Extended Model" are probably simply sparser networks of channels which have similar dimensions. This is based on the observation that many of the single borehole hydraulic tests yielded results indicative of small dimensions (i.e. tubes rather than planes) showing that channels are probably distributed through the rock mass. Hence the conclusion that only in specific zones are they frequent or continuous enough to influence flow over a larger region.

6.3 RELIABILITY OF MODEL

Different aspects of the model of the Crosshole site are described in Chapters 4 and 5. Essential questions concerning the model are to what extent it describes the actual conditions at the site and what predictions can be made from the model.

There is no evidence to believe that significant features exist which have been missed by the investigations performed so far. A few features, e.g. AX, were identified in the radar reflection measurements but were not included in either the Basic or the Extended model. This results from the minimum resolution of the radar reflection method which is smaller than the other techniques defining geometry. When comparing the relative strength of the reflection these zones were considered to be minor. The reflection method is relatively poor at defining exact locations in space and these features may have been confused with others already identified. Overall it is considered that AX was not adequately verified and was therefore omitted. Considering that the Basic and Extended model accounts for all significant geophysical anomalies and most of the hydraulic anomalies the prospects for a zone with a magnitude comparable to that of the zones in the Basic model are small.

The next essential question concerns what types of predictions the model can be used for. The confidence of the model can be considered to be high with respect to the geometry. The radar and seismic methods yield descriptions of the site which agree very well with each other. The tomographic anomalies are found in the same locations even though the tomograms are based on the measurement of independent physical phenomena. This is a strong indication that the features identified in the tomograms are real and not artifacts of the method of investigation. The geometrical description can for example be used to predict where an additional borehole would intersect a specific fracture zone. Predictions could also be made of the width and "contrast" in physical properties at a given location, but this would normally require a further analysis of the radar and seismic data.

The investigations at the Crosshole site have shown that flow is concentrated within fracture zones. Furthermore, flow is confined to channels in the zones. The channeling makes it very difficult to predict the flow through a fracture zone and the local transmissivity that would be measured by a new single borehole intersecting one of the identified zones. The model gives some idea of where groundwater is not likely to be flowing. However, the general direction of movement can be obtained from the head distribution. The current model does not make it possible to predict precise migration paths and transport times as this would require detailed knowledge of the channels within a fracture zone. Such data have not been possible to obtain with the methods applied.

Migration paths could be studied using the radar techniques. If an electrically conductive tracer was added to the groundwater, it might be possible to detect its movement as a change in overall distribution of resistivity. An analysis of singlehole reflection data by methods similar to those used for synthetic aperture radar (SAR) could possibly give data on the variation of electrical properties over the fracture plane.

6.4 IMPLICATION FOR SITE INVESTIGATION STRATEGY

The Crosshole Programme has attempted to correlate between different techniques and assess their ability to identify important features of the groundwater flow system. Whilst it is clearly not possible to dispense with hydraulic investigations by carrying out detailed geophysics, it does seem possible to streamline the hydrogeological approach. Since hydrogeological testing is very time-consuming, this "streamlining" represents a significant portion of site investigation costs. This is possible because, although the geophysical methods do not correctly identify only hydraulically important features, they do not "miss" hydraulic features. Thus hydraulic testing can be concentrated on particular regions, correctly identified by geophysical methods.

If this approach is adopted then experience from the Crosshole Project suggests that care should be adopted in the relative weights given to different techniques. For instance, it would be most efficient (and cheapest) if the minimum of crosshole work was carried out. However, it is clear that the number of identifiable geophysical features decreases with decreasing investigation scale. The same basic rule applies when single borehole reflection radar is compared to crosshole, tomographically interpreted radar measurements. Hence the single borehole radar identifies 59 features compared to 19 features of the "Extended Model" (based largely on tomographic interpretation). Thus if time is saved by using single borehole rather than crosshole geophysical techniques, then extra time will inevitably be needlessly added to the necessary subsequent hydraulic testing.

Another aspect of the testing which would need to be considered in a focussed site investigation is how to bias the hydraulic testing so as to provide the necessary information on groundwater features whilst ensuring that as few features as possible are missed. It seems possible to identify features hydraulically in a number of ways though the only method which will work, if the feature does not intersect the borehole directly, is the head approach. Thus crosshole methods are essential if more information on an intersected feature is desired but are relatively inefficient at identifying channelled features where a high hydraulic conductivity channel does not cut the borehole.

It can be seen, therefore, that the expected nature of the rock is a strong influence in the design of a sensible, conservative, and efficient site investigation procedure. Within the Crosshole Site about 50 % of the recorded flow occurred within one small section of one borehole. In accordance with this general observation the testing tended to assume that flow was concentrated in a small number of zones. Another basic observation of the groundwater flow at the site was that flow occurred within channels within the geophysically identified features. Another site might have a less concentrated groundwater flow system. It is, perhaps, this concentration of flow which enabled the approach adopted on the Crosshole Project to be effective. Therefore the first requirement of an efficient site investigation programme is to gain some measure of how concentrated is the flow. This could be achieved using normal single borehole hydraulic testing. This testing however should be adapted to yield measurements of environmental head. This should be specially emphasized in situation (such as mines) where there are large head disturbances.

The next stage of site investigation would compare the results of single borehole hydraulic testing with single borehole reflection radar. The object of this stage would be to identify any regions of rock where abnormal heads did not coincide with highly permeable features and radar reflections. At the end of this stage there should be fewer anomalous associations than normal ones otherwise a focussed investigation is probably not appropriate.

The last stage would include crosshole geophysics and hydraulics aimed at, both reinforcing the assumptions concerning radar reflectors associated with hydraulic anomalies as well as investigating the "anomalous associations". The tomographic interpretations used in the Crosshole Project seem to be very robust in that they give similar interpretations of both radar and seismic techniques. The sinusoidal testing is rather different in that it is difficult to interpret because it is more sensitive to flow geometry than previously used testing. Simply as a method for "proving connections", it is robust and easy to recognise (in the mine environment) though perhaps limited for range. However, the unique attributes of sinusoidal testing lie in its sensitivity to variations of flow geometry and hence it is a powerful technique in evaluating the flow characteristics of zones already identified. The disadvantage of the technique for this purpose is our limited understanding of how the geometry of sparse networks of channels is translated into derived hydraulic parameters. Thus it is clear that further work is needed before a more detailed appraisal of the flow characteristics of fault zones relevant to nuclide transport can be derived from tests of the sinusoidal type. It is still possible however to envisage a hierarchy of test methods which should be applied sequentially to a site requiring characterization.

The hierarchy would be arranged thus:

single borehole reflection radar - fastest
single borehole hydraulics
crosshole radar
crosshole seismics
crosshole hydraulics
tracer test - slowest

Sites which have highly concentrated flow paths are the type of site which will benefit most from this form of "structured" investigation. These are also the sites with, unfortunately, the greatest risk of important features being missed.

7 CONCLUSIONS

7.1 INVESTIGATION METHODS

7.1.1 Geophysical methods

A major effort of the Crosshole program has been the development of borehole radar and seismic methods. An unique aspect of these methods compared to most other site characterization techniques is that they are based on wave propagation through rock. Investigation methods based on wave propagation have the advantage that they combine high resolution with large range. The resolution that can be obtained is on the order of half a wavelength while the range is determined by the attenuation of the waves. Wave methods are useful if the waves can propagate at least a few wavelengths through the rock. If that is the case they can provide high resolution information at considerable distances from the boreholes.

The borehole radar has been used in three different measuring modes; singlehole reflection, crosshole reflection, and crosshole tomography. These different modes of measurement provide different types of data. The reflection modes basically provide geometric data on features located at a distance from the borehole, in addition the strength of the reflexes give information on the contrast in electrical properties. The reflection method has high resolution and is sensitive even to features with low contrast in properties. The information obtained from a single-hole measurement is cylindrically symmetric with respect to the hole. This implies that the orientation of a fracture zone can not be obtained from measurement in one borehole only. A method has been devised where absolute orientation of fracture zones is obtained by combining single-hole reflection data from a few adjacent holes. Similar methods for analysis of crosshole reflection data have also been developed and found efficient.

The interpretation of the radar results obtained from the three different modes of measurement have yielded a consistent description of the fracture zones at the Crosshole site. The radar has given a resolution of one to three metres. The probing range obtained in the Stripa granite is approximately 100 m in the single-hole mode and 200 to 300 m in the crosshole mode.

The seismic method has mainly been applied in the crosshole tomography mode. Here variations in the arrival time of the direct wave between transmitter and receiver is studied. If a sufficient number of measurements are made between a pair of holes the data set can be inverted to yield a map of the seismic velocity variations in the plane between the boreholes. A new iterative tomographic inversion technique (the Conjugate Gradients or CG-method) has been developed as part of the project. The CG-method has been compared to other iterative inversion methods and found to give shorter computing times and better reconstruction of model examples. The relative reduction in computing time obtained with the CG-method is of particular significance when large data sets are considered.

The tomographic method has less resolution compared to reflection methods but it provides better quantitative estimates of the values of the measured properties. The tomographic methodology and inversion techniques can also be applied to radar data, but here analysis can be made of both travel time and amplitude data which give maps of radar velocity and attenuation, respectively.

An important insight gained during the project is the high quality of the data (travel times or amplitudes) required for obtaining tomograms without significant artifacts. Techniques for quality control and error correction have been devised and successfully implemented. If these techniques are properly applied tomograms are obtained which are representative of the geological structures in the rock and which do not contain artifacts generated by data errors or the inversion procedure.

The distances between the boreholes at the Crosshole site is at most 200 m. Application of both radar and seismic tomography at these separations have yielded positive results. At the Gideå site borehole seismic signals were registered for borehole separations up to 1000 m.

The crosshole seismic data has also been analyzed with respect to reflections in analogy with the radar. After comparatively complex processing a few reflectors could be identified. Crosshole seismic reflection measurements and analysis is considered to have a potential for describing the geologic structure but further development is required.

The success of the radar and seismic methods is best demonstrated by the concordant description these methods have given of the Crosshole Site. These methods have identified regions in this rock volume of decreased velocity and increased attenuation, properties which both are indicative of increased fracturing. The descriptions agree in many essential aspects; the radar and seismic anomalies appear in the same locations, the anomalies obtained from intersecting planes cut at the same location, and the intersection of the features with the boreholes agree with geological and other geophysical observations. The consistency of the description of the Crosshole site obtained by these methods and the agreement with other results is in a sense a proof of that the methods give a real and relevant description of the rock mass and that the anomalies are not some artifact generated by the method itself or data errors.

At the onset of the Crosshole program no borehole radar existed which could give data on geological structures at appreciable distances from the borehole in crystalline rock. During the course of the project the borehole radar has been developed from essentially a set of good ideas into a practically applicable site investigation tool both with respect to performance of measurement and interpretation of data.

The seismic method has also been developed into a practical site investigation tool both with respect to analysis of data and field procedures.

The comparison of the geophysical results with the hydraulic data from the Crosshole site shows that the features identified are of hydrological significance. Hence the data obtained with the geophysical methods are relevant to the nuclide transport problem.

The access to tools like the radar and seismic methods opens new prospects for the investigation of groundwater flow and nuclide transport through fractured crystalline rock. An important aspect is the possibility to obtain high resolution data on the structure and extent of fracture zones. This could improve the understanding of processes like faulting, lateral variations in the properties of fracture zone, and channeling of groundwater flow within fractures or fracture zones. Data of this type will have bearing on how nuclide transport models are constructed and the reliability of the data that are used as inputs into the models.

7.1.2 Hydraulic methods

The hydraulic investigations within the Crosshole project have yielded substantial progress in assessing the hydrogeology of fractured granitic rocks. This has resulted from improvements concerning three aspects of hydraulic testing. Firstly the approach to testing has been improved by planning based on reliable geometric information about the whole region to be tested. Secondly the instrumentation used in the testing was computer based resulting in better adherence to interpretation assumptions and improved control over test conditions. Thirdly the testing has demonstrated the application of an improved and feasible interpretation concept which is more appropriate to fractured rocks than previous concepts derived from sedimentary rocks.

As the results of the geophysical measurements were combined with the initial single borehole hydraulic measurements, it became clear that testing effort needed to be focussed on the zones of greatest potential flow. The crosshole testing therefore concentrated on measuring the distribution of hydraulic properties within the extensive fractured zones. Additionally a testing approach using sinusoidally varying pressure and flow rate was adopted to minimise times waiting for the tested zones to regain their pretesting head. This approach for causing a minimum long-term head disturbance during testing was applied throughout the Crosshole programme (i.e. in both single and crosshole testing). It was seen to be effective in reducing waiting times and improving background conditions. The sinusoidal approach to crosshole testing was also seen to be useful in the mine environment since a signal of known frequency is easily observed even against rapidly fluctuating background.

The sinusoidal hydraulic signal was generated by a specially designed and constructed set of computer controlled equipment.

The equipment had several features which were very useful in the mine environment. Firstly, it was possible to generate a precisely controlled signal which conformed closely to the assumptions involved in the analysis of the data. Secondly, the position of the signal was precisely known and the second set of pumps to control the head in the rest of the borehole was extremely effective. In combination with the sinusoidal technique, it was possible, by examining whether there was any sinusoidal variation in the pumping to the rest-of-borehole zone, to evaluate the effective leakage around the packers.

Another advantage of the computer control system was the ability to measure to great accuracy using the progressive differential pressure approach. This approach would have been impossible by hand and would have given rise to mistakes which would have damaged some of the components.

In summary, the use of micro-computer to control as well as record tests yielded benefits in improving the quality of the data gathered. The total system which included a novel device to seal the ends of the boreholes resulted in a larger data set being gathered in a limited period.

The form of crosshole hydraulic testing used in the project; that of sinusoidal testing, is sensitive to the geometry of the flow system being tested. When this is poorly known and complex then it is inevitable that only a small number of tests are analyzable. In order to increase the number of well-interpreted tests a new interpretation system based on fractional dimensions has been devised. This analysis uses data from crosshole sinusoidal tests as input to a variable geometry model and derives the apparent "dimension" of the tested flow system in addition to the more usual hydrogeological parameters. Essentially the analysis assumes that there is a continuous spectrum of geometry in between the well-known forms such as 2-D (radial flow in a plane) and 3-D (spherical flow within a porous medium). This is a versatile analysis well-suited to the sort of flow geometries likely to be found in fractured crystalline rocks. It was found that responses were frequency dependent but detailed interpretation of this phenomenon is not yet possible.

The hydrogeology of channelled fractured rocks is broadly understood but relatively poorly investigated in the field. The problem arises from the scale of possible tests. At small scales, such as single borehole hydraulic tests, the flow system can be equated to relatively simple geometries. At the largest scale the rock should behave as an equivalent porous medium. At intermediate scales, such as crosshole testing, the "sparse network" problem arises where test interpretations are particularly difficult.

The hydraulic testing in the Crosshole project has shown some of the possibilities in this field of work. The combination of geophysics with hydrogeology is extremely productive in helping to define problems and focus testing.

7.2 GROUNDWATER FLOW

The aim of the Crosshole project was to characterize the rock and fractures of the Crosshole site in order to predict the flow of groundwater in fractured granite. A number of different techniques were used to examine the flow of groundwater which resulted in observations at different scales.

At the largest scale (the scale of the hole site), the presence of the "old drift" caused a known head disturbance which was observable at distances up to several hundred metres. The highly variable patterns of head distribution seen in the six boreholes showed that a few "special features" (identified broadly as fracture zones) determined the flow of groundwater within the whole site. Moreover, the fractured granite at Stripa cannot be considered as an anisotropic medium with continuous directional properties.

A series of detailed crosshole sinusoidal tests were carried out to examine the hydrogeological character of two of these fracture zones. These tests showed that, even within the fracture zones, flow was apparently localized to a system of interconnecting channels. The nature of these networks of channels is complex and they differ from zone to zone. The flow testing determined a dimension for these networks which showed that Zone C seemed to have a sparser network of channels and interconnections than Zone A. The testing also indicated that where fracture zones bifurcated they tended towards lower hydraulic conductivity. The hydraulic conductivity derived from single borehole tests within these zones was in the region of $5\ 10^{-8}$ m/s on average.

The crosshole geophysics indicated that the fracture zones consisted of "patches" of more porous rock which were roughly aligned. The patches generally had a major dimension several times larger than the minor dimension. Although it was possible, where crosshole tomograms crossed, to observe these fracture zones in more than one plane, it was not possible to observe the nature of interconnection of patches. Radar reflection measurements tended to over-emphasize the planar nature of fracture zones.

In between the fracture zones which dominate the large scale flow of groundwater, the rock is regularly fractured and some flow occurs within these fractures. This rock was only investigated using single borehole hydraulic tests but again the tests often indicated flow within channels. The testing was not sufficiently detailed to yield the frequency of "active" fractures of channels but it is certainly less than the number of fractures observed by core logging. Analysis of the tests indicated a hydraulic conductivity for this "averagely fractured rock" of about 2 10^{-10} m/s. This can be compared to unfractured rock which appears to have a hydraulic conductivity around 10^{-11} m/s. However, this value for matrix rock is probably higher that the value which would be measured in the laboratory because it is essentially the material immediately adjacent to the fractures. This may be slightly altered granite rather than the intact rock measured in laboratory experiments.

Overall, the testing showed the need to have a clear idea of the geometry of a potential flow feature before testing. This was because important regions of flow were sparse and spatially comprehensive testing is not possible within conceivable time scales. Additionally the concept of geometry used to interpret the flow test severely influences the values of hydraulic conductivity derived from the results. The hydraulic testing carried out within the programme would have been impossible to organize or interpret without the information provided by the geophysical techniques.

7.3 IMPLICATIONS FOR SITE INVESTIGATIONS

The Crosshole project has demonstrated that there is an optimum structure in a programme of site investigation. This structure needs to ensure that each technique not only expands on information gained earlier but also produces information which is usable later on. The questions of scale and resolution are important to this structure.

In site investigations for radioactive waste, the data will inevitably be used as input to a three dimensional predictive model. The site investigation therefore requires data on the geometry of the site and the distribution of properties within it. Either in the precise region of the repository or wherever the model is to be validated, the model must be capable of reliable and detailed predictions. Hence there must be a structure of increasingly detailed investigations in both time and space.

The first aim of the site investigation programme must be to define the geometry of the major features. Experience from this project shows that the distribution of the major features is identified best by a combination of single borehole reflection radar and tomographic inversion of crosshole radar and/or seismic data. Once these features are identified the second aim can be approached: that is to describe the distribution of important properties such as hydraulic conductivity. This is best achieved by crosshole hydraulic testing even though it is extremely time consuming. In order to solve this problem of time and cost it is necessary to focus the crosshole hydraulic testing on the major features by testing within them. The scales of all these crosshole techniques are relatively large whilst resolution is comparatively coarse. This is most appropriate when the site investigation is at a general level.

The detail of the site investigation can be increased considerably by using the data from high frequency single borehole radar in reflection mode. However, the ability to correlate the smaller radar features with hydraulic parameters is currently not well developed. In general the single borehole radar reflection method indicates more features than are picked out by single borehole hydraulics. The correlation may be improved in the future.

The Crosshole Project has shown that it is possible to characterize fractured crystalline rock with a reliability and realism not attained before. The same approach should be adopted in future site investigations for radioactive waste disposal.

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