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TECHNICAL REPORT 87-37

CROSSHOLE INVESTIGATIONS – HYDROGEOLOGICAL RESULTS AND INTERPRETATIONS

JOHN BLACK
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DECEMBER 1987

BRITISH GEOLOGICAL SURVEY
UNITED KINGDOM

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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 was an integrated geophysical and hydrogeological study of a limited volume of rock (known as the Crosshole Site) within the Stripa Mine. Borehole radar, borehole seismic and hydraulic methods were developed for specific application to fractured crystalline rock.

The hydrogeological investigations contained both single borehole and crosshole test techniques. A novel technique, using a sinusoidal variation of pressure, formed the main method of crosshole testing and was assessed during the programme. The strategy of crosshole testing was strongly influenced by the results from the geophysical measurements.

The single borehole testing comprised roughly equal amounts of constant head and slug/pulse testing. Transmissivities varied between values around 1×10^{-12} m^2 sec^{-1} and 5×10^{-7} m^2 sec^{-1}. For the most part high transmissivities were associated with geophysically identifiable fracture zones. Test zone lengths varied between 2 and 13m and few tests were interpretable as single fissure responses.

The crosshole sinusoidal testing was carried out using computer-controlled test equipment to generate the sinusoidally varying head in a single zone (the "source") isolated by packers. A second ("receiver") borehole contained a number of straddle intervals and was used to observe the propagation of the sinusoidal signal. The number of positive responses was limited and flow appeared to be concentrated within a few "channels". Analysis was attempted using single fissure, regularly fissured and porous medium models. None gave satisfactory fits to the measured data. A new analysis involving the "dimension" of the flow test has been developed to analyse the results of the crosshole sinusoidal testing. This yields results involving "fractional dimensions" where flow may be asumed to occur within regions which do not fit within the existing 1, 2, and 3 dimensional models. This is a versatile analysis, well-suited to the sort of flow geometries likely to be found in crystalline rocks.

The longer term, larger scale hydrogeological response of the region was asessed by examining the variation of heads over the region. These were responding to the presence of an old drift. A method of overall assessment involving minimising the divergence from a homogeneous response yielded credible values of hydraulic conductivity for the rock as a whole.

RESUME

Le programme Crosshole (entre puits) a permis de procéder à l'étude géophysique et hydrogéologique intégrée d'un volume rocheux limité, appelé "site Crosshole", à l'intérieur de la mine de Stripa. Des techniques de radar et de sismique de forage ainsi que des méthodes d'investigations hydrauliques ont été mises au point en vue de leur application spécifique à la roche cristalline fracturée.

Les études hydrogéologiques ont compris des méthodes d'essais de forage simple et de forage entre puits. La partie principale des essais entre puits a consisté en une nouvelle technique recourant à une variation de pression sinusoïdale; cette technique a été évaluée au cours du programme. Les résultats des mesures géophysiques ont sensiblement influencé la stratégie des essais entre puits.

Au cours de l'expérience du puits de forage simple, on a procédé à des essais avec hauteur manométrique constante, ainsi qu'à des tests Slug/Pulse. Les transmissivités ont varié entre $1x10^{-12}$ m^2 sec^{-1} et $5x10^{-7}$ m^2 sec^{-1} environ. On a associé la majeure partie des transmissivités élevées à des zones de fracture identifiables par la géophysique. La longueur de la zone de test a varié entre 2 et 13 m, et seuls quelques rares essais ont été interprétés en tant que le résultat d'une seule fissure.

On a réalisé l'expérience entre puits avec signaux sinusoïdaux à l'aide d'un équipement commandé par ordinateur, afin de provoquer la hauteur manométrique avec variation sinusoïdale dans une seule zone ("émetteur") isolée par des obturateurs. Un second puits de forage ("récepteur"), contenant plusieurs intervalles d'obturateurs, a permis d'observer la propagation du signal sinusoïdal. Le nombre de signaux de réponse positifs a été limité et l'écoulement a semblé se concentrer sur quelques rares "canaux". On a tenté l'analyse en recourant à différents modèles: fissure unique, fissuration régulière et milieu poreux. Aucun n'a concordé de manière satisfaisante avec les données mesurées. Une nouvelle méthode d'analyse, comprenant la "dimension" de l'écoulement, a été mise au point pour évaluer les résultats des essais entre puits avec signaux sinusoïdaux. Cette méthode fournit des résultats comprenant des "dimensions fractionnées", où l'on suppose que l'écoulement se produit dans des zones ne pouvant pas être décrites avec les modèles existants à 1, 2 et 3 dimensions. Cette analyse variée convient particulièrement bien aux géométries d'écoulement que l'on trouve dans les roches cristallines.

On a analysé l'hydrogéologie à plus long terme et sur une plus large échelle de la région, en observant la variabilité des hauteurs manométriques dans la région. Elles ont mis en évidence l'influence d'une ancienne galerie. Une méthode d'évaluation globale, réalisée en minimisant l'écart d'un signal de réponse homogène, a donné des valeurs fiables pour la conductibilité hydraulique moyenne de la formation rocheuse.

ZUSAMMENFASSUNG

Mit dem Crosshole-Programm wurde eine integrierte geophysikalische und hydrogeologische Studie eines begrenzten Gesteinsvolumens (der sogenannte "Crosshole-Standort") in der Stripa Mine durchgeführt. Das Bohrlochradar, die Bohrlochseismik und hydraulische Untersuchungsmethoden wurden für spezifische Anwendungen im geklüfteten kristallinen Gestein entwickelt.

Die hydrogeologischen Untersuchungen umfassten sowohl Einbohrloch- als auch Crosshole-Testverfahren. Der Hauptteil des Crosshole-Experiments bestand aus einer neuen Technik mit sinusförmiger Druckveränderung; diese Technik wurde im Laufe des Programmes evaluiert. Die Strategie zur Durchführung der Crosshole-Tests wurde stark durch die Ergebnisse der geophysikalischen Messungen beeinflusst.

Das Einbohrlochexperiment umfasste Versuche mit konstanter Druckhöhe- sowie Slug/Pulse-Tests in etwa gleichen Anteilen. Die Transmissivitäten lagen zwischen ca. $1x10^{-12}m^2sec^{-1}$ und $5x10^{-7}m^2sec^{-1}$. Hohe Transmissivitäten waren zum grössten Teil mit geophysikalisch nachweisbaren Kluftzonen assoziiert. Die Länge der Testzone variierte zwischen 2 und 13 m und nur wenige Tests konnten als Einzelkluft-Resultate interpretiert werden.

Das Crosshole-Experiment mit sinusförmigen Signalen wurde mit computergesteuerter Instrumentierung durchgeführt, um die sinusförmig variierende Druckhöhe in einer einzelnen durch Packers isolierten Zone ("Sender") zu erzeugen. Ein zweites ("Empfänger") Bohrloch enthielt mehrere Packerintervalle und diente dazu, die Fortpflanzung des sinusförmigen Signals zu beobachten. Die Zahl der positiven Antwortsignale war beschränkt und der Fluss schien sich auf einige "Kanäle" zu konzentrieren. Die Analyse wurde mit verschiedenen Modellen versucht, Einzelkluft, regelmässige Klüftung und poröses Medium, aber keines davon ergab eine zufriedenstellende Übereinstimmung mit den gemessenen Daten. Ein neues Analyseverfahren, welches die "Dimension" des Flusses umfasst, wurde entwickelt, um die Resultate der Crosshole-Tests mit sinusförmigen Signalen zu evaluieren. Dieses Verfahren liefert Resultate mit "gebrochenen Dimensionen" wobei angenommen wird, dass der Fluss in Zonen stattfindet, die nicht mit den existierenden 1-, 2-, und 3-dimensionalen Modellen beschrieben werden können. Diese vielseitige Analyse ist besonders geeignet für die Fliessgeometrien, die in kristallinen Gesteinen gefunden werden.

Das langfristige, grossräumige hydrogeologische Verhalten des Gebiets wurde durch eine Beobachtung der Variabilität der Druckhöhen in dem Gebiet beurteilt. Diese zeigten den Einfluss eines alten Stollens. Eine Methode zur Gesamtbeurteilung durch Minimierung der Abweichung von einem homogenen Antwortsignal lieferte zuverlässige Werte für die durchschnittliche hydraulische Leitfähigkeit des Gesteinskomplexes.

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SUMMARY

The hydraulics programme of the Crosshole Project had roughly two aims, to "calibrate" the geophysical methods and to evaluate sinusoidal testing. The calibration of the geophysical methods is described in another report (Olsson and others, 1987).

The programme consisted of

1) the development of a novel set of test equipment
2) single borehole tests (including slug, pulse and constant head/flow techniques)
3) crosshole tests (mainly sinusoidal but also constant flow techniques)
4) the development of a novel test interpretation for fractured rocks (fractional dimensions)
5) an assessment of large scale responses based on head variations

The programme showed that it is possible to design and construct a complex set of computer-controlled equipment and operate it regularly in the mine environment. The innovative aspects of the equipment were the use of a computer for test operation. This resulted in good quality data with a high resolution and a close adherence to the analytical assumptions underlying the test.

The single borehole testing was relatively standard in the techniques which were employed but was slightly hampered by the mixture of equipment and contractor which occurred. The mean and average hydraulic conductivities of the six boreholes were comparatively similar differing by no more than an order of magnitude between the least (average $K = 2x10^{-10}$ m sec^{-1})and the most (average $K = 2x10^{-8}$ m sec^{-1}) conductive. Within these general statistics there was a general trend from least conductive in the North to most conductive in F6 in the South. Also it should be pointed out that one zone accounted for over 50% of the measured transmissivity of all the boreholes.

The sinusoidal testing had attributes which were not expected. Firstly it proved very easy to create a sinusoidal fluctuation since it requires neither rapid changes of flow rate or head or long periods of steady conditions. The computer produced sinusoidal fluctuations which were ideal. The main unexpected aspect of sinusoidal testing is its sensitivity to the correct assumption concerning the geometry of flow during a test.

The analysis of the sinusoidal tests resulted in a new analysis having to be adopted. The development of the fractional dimension analysis represents a first step towards flow concepts which have a universal application. It seems possible that it represents a practical method for deriving general hydraulic properties of channelled fracture zones.

On a practical level it appears that many tests have been misinterpreted in terms of a 2-D response where some dimension closer to 1-D would have been more appropriate. There is evidence in the tests reported here that some of the slug and pulse tests contained a response which probably resulted from flow in channels. In general it is clear that the fractional dimension approach requires further investigation.

Another aspect of analysis which deserves further work is the steady state approach to the measurement of the large scale heterogeneity. It contains an aspect of remote sensing which is not contained in other hydraulic testing techniques. Briefly the use of head data to pinpoint anomalous rock either intersecting the borehole or closeby provides a method for checking the zones of interest selected by geophysical methods.

The Crosshole Site proved ideal in its behaviour as a fractured rock. It was seen that the rock is quite regularly fractured though around 10% of the tested length yielded results indicative of unfractured rock. The matrix rock had a K of $1x10^{-12}$ m sec^{-1} and a specific storage of $1x10^{-6}$ m^{-1}. In the vicinity of fractures this may well rise by an order of magnitude.

The bulk of the rock does not take part in regional flow. Instead it is concentrated to particularly active channels contained loosely within fracture zones. Of the two zones investigated by the crosshole sinusoidal method, Zone A appears to have a larger dimension than Zone C. This may indicate that Zone C is a sparser network of channels than Zone A.

A major result of the Crosshole Hydraulic Programme has been the necessity to re-examine many hydrogeological preconceptions.

1 INTRODUCTION

1.1 GENERAL BACKGROUND

The Crosshole Programme of Phase II of the Stripa Project has as a general objective the development of non-destructive site-characterisation methods for potential radioactive waste repositories. More particularly, the programme consists of using three separate techniques (radar, seismic and hydraulic) in the same volume of rock at the Stripa Mine in central Sweden. The intention was to compare the results and assess how well the remote sensing methods (seismic and radar) could be used to predict the groundwater flowpaths.

During the years 1983-1986 these three techniques have been deployed within the six boreholes which make up the "fan-array" of the Crosshole Site. There are therefore three almost separate pieces of work consisting of:

- radar investigations
- seismic investigations
- hydraulic (meaning physical hydrogeology) investigations

In addition to these applications of particular techniques there has also been a preliminary phase of site description (Carlsten and others, 1985) and a detailed description of the cores from the six boreholes (Carlsten and Stråhle, 1985). However, the three investigation techniques form the core of the programme and are reported separately as well as together. This report is the summary report of the hydraulic investigations.

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. These novel aspects are reported separately. Hence the equipment is described by Holmes (1984) and by Holmes and Sehlstedt (1987). The interpretation of sinusoidal pressure tests is described by Black and others (1986) and by Noy and others (1987). In this report therefore, it is intended to describe the work that has been carried out, outline the results and interpret them in terms of the physical hydrogeology of the Crosshole Site.

1.2 EXPERIMENTAL SITE

The Crosshole Site is a specially prepared experimental site 360m below surface in the Stripa Mine. Six boreholes have been drilled from essentially the same position at the end of a drift. The boreholes are drilled in a "fan-like" fashion so that they roughly outline a tilted pyramid with a height of approximately 200 m and a base of roughly the same length (Figure 1.1). The boreholes named F1, F3, and F5 are 200m long and dip downwards at about 10° to the horizontal. The

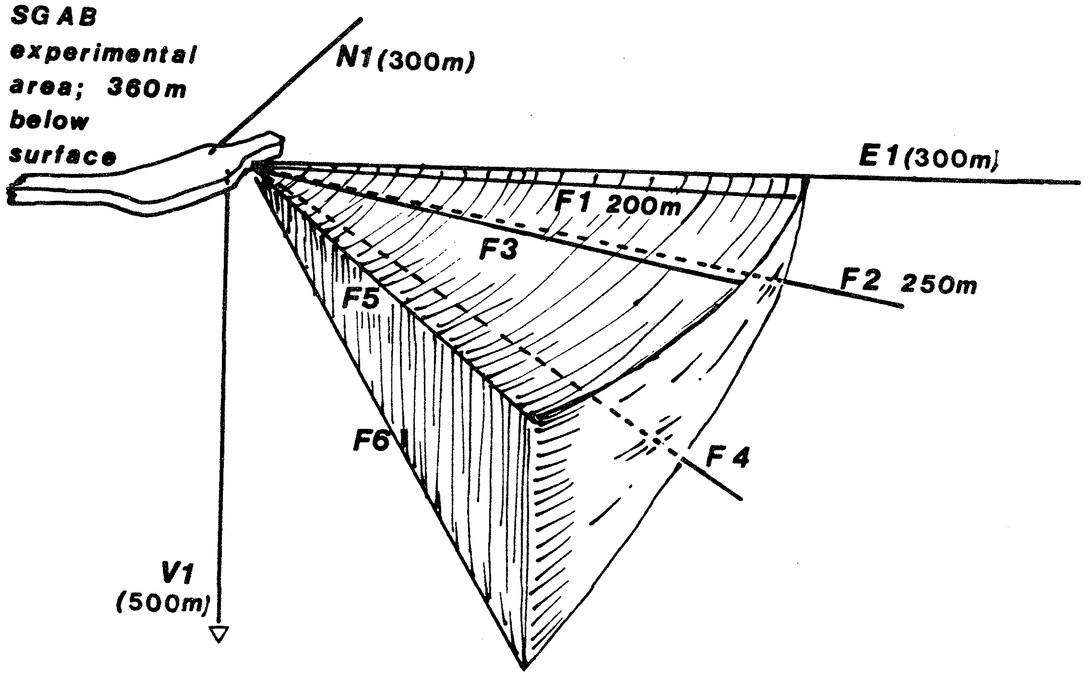


Figure 1.1 The "fanlike" array of boreholes at the Crosshole Site

angle of separation between them is also 10°. The boreholes named F2, F4 and F6 are all 250m long but dip more steeply downwards than the "top fan". Thus F2 dips at 20° to the horizontal, F4 at 30° and F6 dips most steeply at 40°. Another symmetry within this system of boreholes is that F2 lies vertically beneath F1, F4 beneath F3 and F6 beneath F5.

The site is shown in plan in Figure 1.2. where the layout of the fan can be seen in

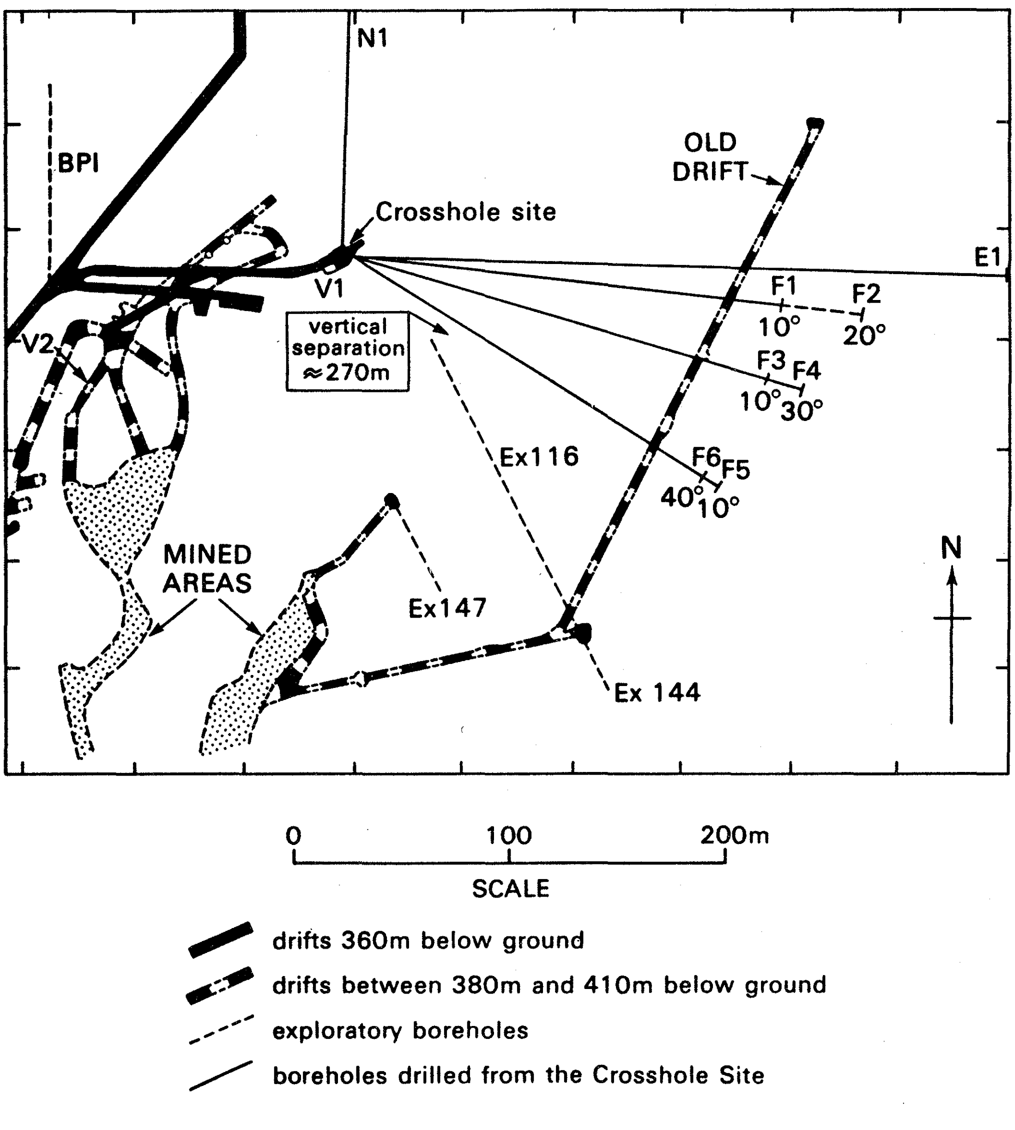


Figure 1.2 Plan view of the Stripa Mine at the 360m and 410m levels showing the position of the investigatewd boreholes F1 to F6 (from Carlsten and others, 1985).

relation to the disposition of the old mined-out areas and the old exploration drift which penetrates between the top and the bottom arrays of the fan. The mined areas reportedly reach a maximum depth of about 420m below surface and pumping maintains the water level within them at about 410m below surface.The drifts to the western edge of Figure 1.2 form a system of inclined roadways linking the levels at 360m and 410m below surface (known as the "360 level" and the "410 level"). The exploratory boreholes, marked as Ex 147 and Ex 116, both dip downwards at angles of 43° and 60° respectively. Thus although Ex 116 appears to converge with F5 and F6, they are in fact separated by considerable vertical distances. The vertical separation between the end of Ex 116 and F6 is about 270m at the position marked in Fig. 1.2. Other features which might influence the hydrogeology of the Crosshole Site are the "3-D Drift" situated in the N.W. corner of Fig. 1.2 and the rest of the mine which lies entirely to the south of the map shown in Fig. 1.2.

1.3 OUTLINE OF THE HYDROGEOLOGICAL WORK

The Crosshole Project began in 1983 and site work was completed by early summer 1986. During this period all three techniques (i.e. radar, seismics and hydraulics) have been deployed within the six fan-array boreholes for varying durations. There was also an initial phase of work aimed at a basic characterisation of the site using core logging and single borehole geophysics. This initial phase was also intended to include a comprehensive series of single borehole hydraulic tests carried out by S.G.A.B. (Swedish Geological Company) but this was eventually undertaken in 4 of the 6 boreholes by B.G.S (British Geological Survey).

The hydrogeological work can be divided into two types: single borehole and "crosshole" (between boreholes). All tests were carried out in zones isolated from the rest of the borehole using packers.

The testing comprised the following parts:

type of testing	Operator	boreholes tested
single borehole [constant head injection]	S.G.A.B.	F1 & F2
single borehole [pulse, slug and constant head: injection & abstraction]	B.G.S.	F3, F4, F5 & F6
crosshole [constant rate injection and sinusoidal]	B.G.S.	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 hydraulic testing began. 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 targetted 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 23 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.

2. BACKGROUND TO HYDRAULIC TESTING

2.1 INTRODUCTION

The hydraulic testing carried out within the programme consisted of both relatively standard testing (the single borehole tests) and some novel tests (the sinusoidal testing). The testing equipment used by B.G.S. was also unusual. The intention in this section is to provide the minimum of background on the "standard" techniques and give more emphasis to the novel aspects of the testing.

2.2 BASIC THEORY OF FLOW TESTS

All the testing within the programme assumes that Darcy's Law is valid. This states that the rate at which water flows through a unit volume of rock in response to a unit head gradient is determined by its hydraulic conductivity(K). This relationship can be used directly to determine hydraulic conductivity when head gradient is constant and flow is in steady state. In practice, steady state situations are generally found at large scales. In contrast, testing in boreholes is usually on such a short time scale that steady state is not reached and a non-steady state flow system is involved. To derive values of hydraulic conductivity from such "transient" tests, Darcy's Law is combined with the law of conservation of mass. In essence, this quantifies the amount of water stored in unit volume of rock per unit change of head and is termed (in hydrogeological terminology) the specific storage(S_s). By combining the two laws it becomes possible to describe the rate of propagation of a "hydraulic signal". This is dependent on the hydraulic diffusivity (K / S_s). In order to derive hydraulic conductivity from measurements of hydraulic diffusivity it is necessary either to know, or to assume, a geometry for the system being tested.

It is assumed in the interpretation of hydraulic tests within these investigations that all tests are conducted remote from significantly large water tables so that storage of water within the rock occurs as elastic storage within compressible rock. It is further assumed that the specific storage of the rock is not dependent on absolute stress since all tests have been performed within a relatively narrow band of total stress. A further simplification assumes that the hydraulic conductivity is also independent of absolute stress. This is for the same reason as the assumption is applied to specific storage.

In this report, the following quantities, symbols and units are used:

quantity	symbol	units
head	h	m (of water above stated datum)
hydraulic conductivity	K	m sec^{-1}
specific storage	S_s	m^{-1}
flow	Q	m^3 sec^{-1}

2.3 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 a 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.

2.3.1 Constant head/flow tests

Almost all of the "constant" type tests were of the constant head variety. This included the tests carried out in the initial stages by S.G.A.B. in boreholes F1 and F2. A 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, (1985a) and consisted of a two hour period of injection at 100m 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 by S.G.A.B. the excess head is imposed by using a gas overpressure system. In the constant head testing carried out by B.G.S. the excess head varied between 10m and 25m and was imposed either using water added to an open tube or using servo-assisted ram pumps controlled by computer. The flow rate is measured in the S.G.A.B. system by a series of flowmeters arranged in parallel to cover the range of flow rates encountered. These meters are read manually. The computer-controlled equipment records the flow rate automatically and derives it from knowing the movement of the ram within the pump. Similar injection and recovery periods were used, though, in general the B.G.S. testing involved shorter periods between zone isolations. This meant lesser fluctuations in borehole pressure and, in consequence, shorter and more reliable pre-injection periods for the measurement of environmental head.

The single-borehole constant head test can be analysed in three ways. The first, and simplest, way is to use the "steady-state" value of flow rate which was measured at the end of the period of injection. This is commonly known as the "steady-state" method and examples are outlined in Braester and Thunvik, (1982). Based simply on Darcy's Law, it assumes a cylindrical flow field centred on the single source borehole. It only yields values of hydraulic conductivity. A drawback of the method is the slow approach to steady state in zones of very low transmissivity (i.e. hydraulic conductivity times zone length:- KL).

The second method derives results for both K and S_s by analysing the change of flow rate with time. Most well test analysis is of this type and a full description of the various approaches was given by Carlsson and Olsson, (1985a). Usually the injection and recovery phases of the test are analysed separately and the results compared. The third method involves analysing the injection and recovery phases together as a single test. This is usually in the form of numerical modelling using a "well simulator".

The analysis methods applied to this form of testing have been compared in detail by Carlsson and Olsson, (1985a). They do not examine well simulators since data gathered in low K rocks seldom justify such a rigorous approach. Recent work by Andersson and Persson, (1985) expands the consideration of the reliability of the "steady-state" versus the "transient" based results from the whole of the Swedish testing programme. It confirms the trends observed by Carlsson and Olsson, (1985c) where the steady-state result is an overestimate at low K values (see Figure 2.1).

There are an equivalent set of analyses for constant flow tests (see Karasaki, 1986).

In general the results from the S.G.A.B. testing of F1 and F2 were analysed using the transient method. The B.G.S. constant head tests in F6 and highly conductive zones in other boreholes were analysed using Moye's formula (a steady-state formula evaluated by Braester and Thunvik, [1982]).

2.3.2 Pulse and slug tests

Pulse and slug tests were carried out only by B.G.S. using the computer-controlled equipment (see Section 2.4) 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

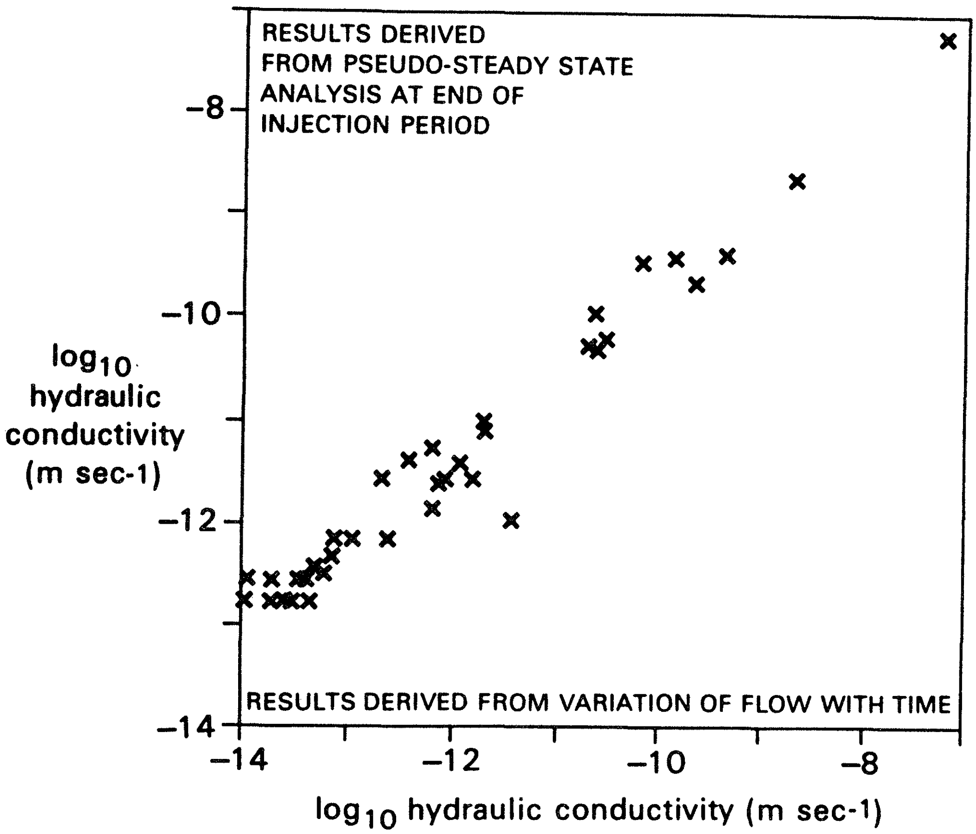


Figure 2.1 A comparison between hydraulic conductivity derived from constant head tests using steady state and transient methods (from Carlsson and Olsson, 1985a).

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 25mm I.D. aluminium tubing whilst the receiver zones had a 200-240m length of 3mm 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 (Figure 2.2) was in fact quite similar because the larger volume steel tubing was less elastic than the 3mm 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

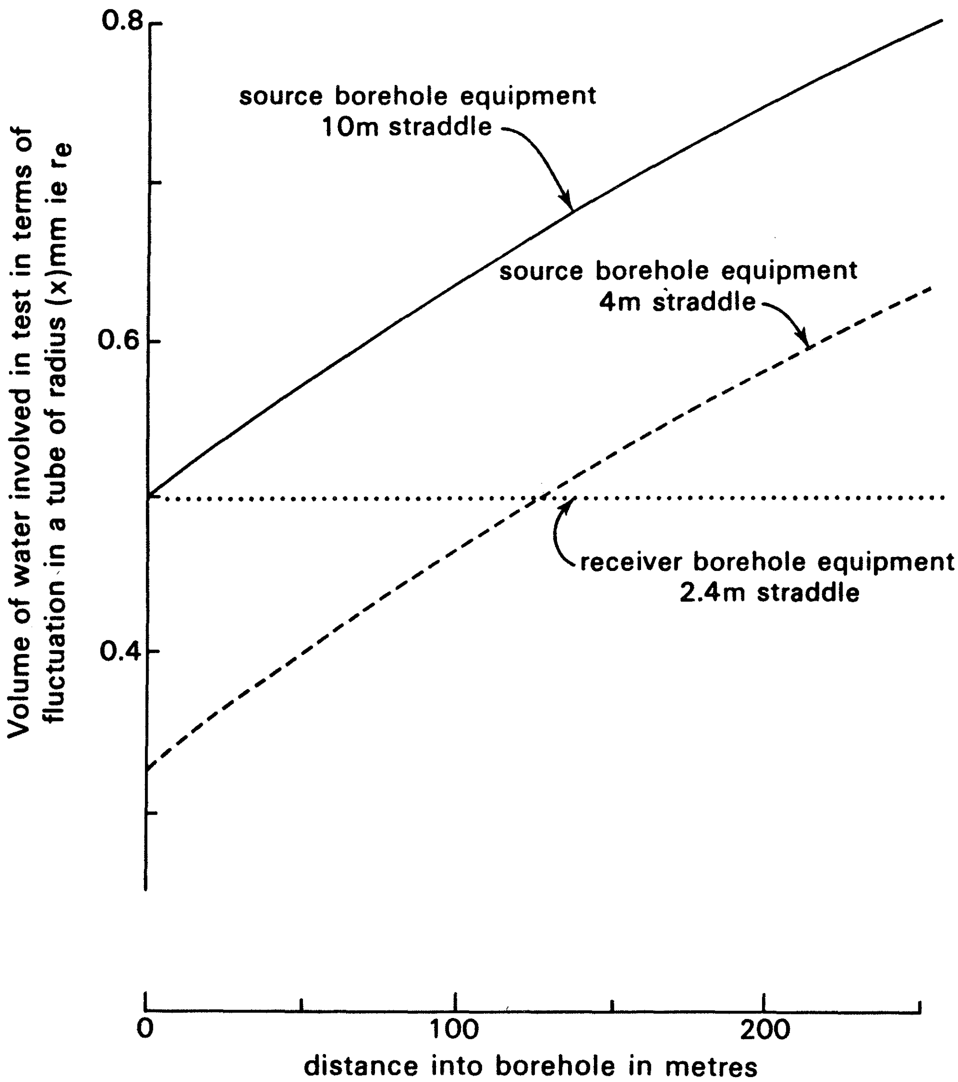


Figure 2.2 The volume of water per unit head change involved in pulse tests versus position of the testing string in the borehole. The volume is expressed in terms of the radius of a unit length of incompressible tube.

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 (see Section 2.4.2.4) was utilised so that, after the initial head disturbance, the head recovered in the form of a water level moving within a 8mm 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. The "reference pressure" system consisted of a 600m long length of 8mm I.D. plastic tubing running from the instrument drift along the access tunnel and up a ventilation shaft. The level of water in this tubing could be adjusted to any level. Immediately prior to slug tests, the level was adjusted so that it was within +/- 1 metre of the environmental head of the test zone.

These two forms of test had effective ranges of applicability. Hence slug tests were most appropriate for transmissivities between $5x10^{-7}$ to $1x10^{-9}$ m^2sec^{-1}. The lower limit is a question of duration whilst the upper limit results from the problem of excessive head loss in the pipework. Pulse tests were best when transmissivity was less than $1x10^{-8}$ m^2sec^{-1} . When transmissivity exceeded $1x10^{-7}$ m^2sec^{-1} 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 (for which there is a growing literature) 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 and others, 1967) plus the compliance of the system. The compliance of the system is usually negligible compared to r_c. For a pulse test, where the test zone is shut-in, the amount of water involved in a unit change in head is the volume of water in the borehole (between the shut-in valve and the responding section) multiplied by the compressibility of water, plus the compliance of the system. This gives the equation of Bredehoeft and Papadopulos (1980) :

$$r_c^2 = V_w C_w \rho_w g / \pi \qquad [1]$$

where V_w is the enclosed volume of water (e.g. m^3)
C_w is the compressibility of water (e.g. $Pascals^{-1}$)
ρ_w is the density of water (e.g. $kg\ m^{-3}$)
g is the acceleration due to gravity (e.g. $m\ sec^{-2}$)

In Black (1985) the concepts of the specific storage of water (S_{sw}) and the effective radius of a slug/pulse test were introduced where:

$$S_{sw} = C_w \rho_w g \qquad (\approx 5 \times 10^{-6}\ m^{-1}) \qquad [2]$$

and

$$r_e^2 = (V_w S_{sw} + sc) / \pi \qquad [2a]$$

where r_e is the "effective radius" of a slug/pulse test
sc is the volume compliance of the system per unit head change

Hence, if the pressure on the enclosed water in the test zone is changed by a metre of water head, the amount of water involved in flowing into or out of the test zone will be $V_w S_{sw} + sc$; which is equivalent to water movement within a fine incompressible tube whose radius is r_e. For a 10m long straddle in a borehole of 76mm diameter and without system compliance, the value of r_e will be about 0.3mm (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 0.3mm so that values for the total system with the minimum of downhole tubing amounted to about 0.45mm ($\sqrt{[0.3^2] + [0.3^2]}$).

2.3.3 Crosshole constant flow tests

Very few crosshole constant flow tests (usually termed aquifer or interference tests) were carried out. It has exactly the same form as the single borehole version except that the head is 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. However, in contrast to the sinusoidal testing, it was generally carried out using long lengths of borehole as source and observation zone. The duration of the constant flow period varied; the longest period used being 2 days. An important aspect of these tests was the need to know broadly the conductivity of the source zone so as to make an estimate of the head likely to be reached in the source zone by the end of the test. This had to be within reasonable rock and equipment limits and was usually set at about +/-20m. 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. There are a large number of possible interpretations of the flow geometry based on the details of the head versus time response. These are examined, together with the practical difficulties of applying the technique in the Stripa Mine, by Carlsson and Olsson, (1985a and 1985b).

2.3.4 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 2.3a). 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 2.3b). 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:

Advantages:

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.

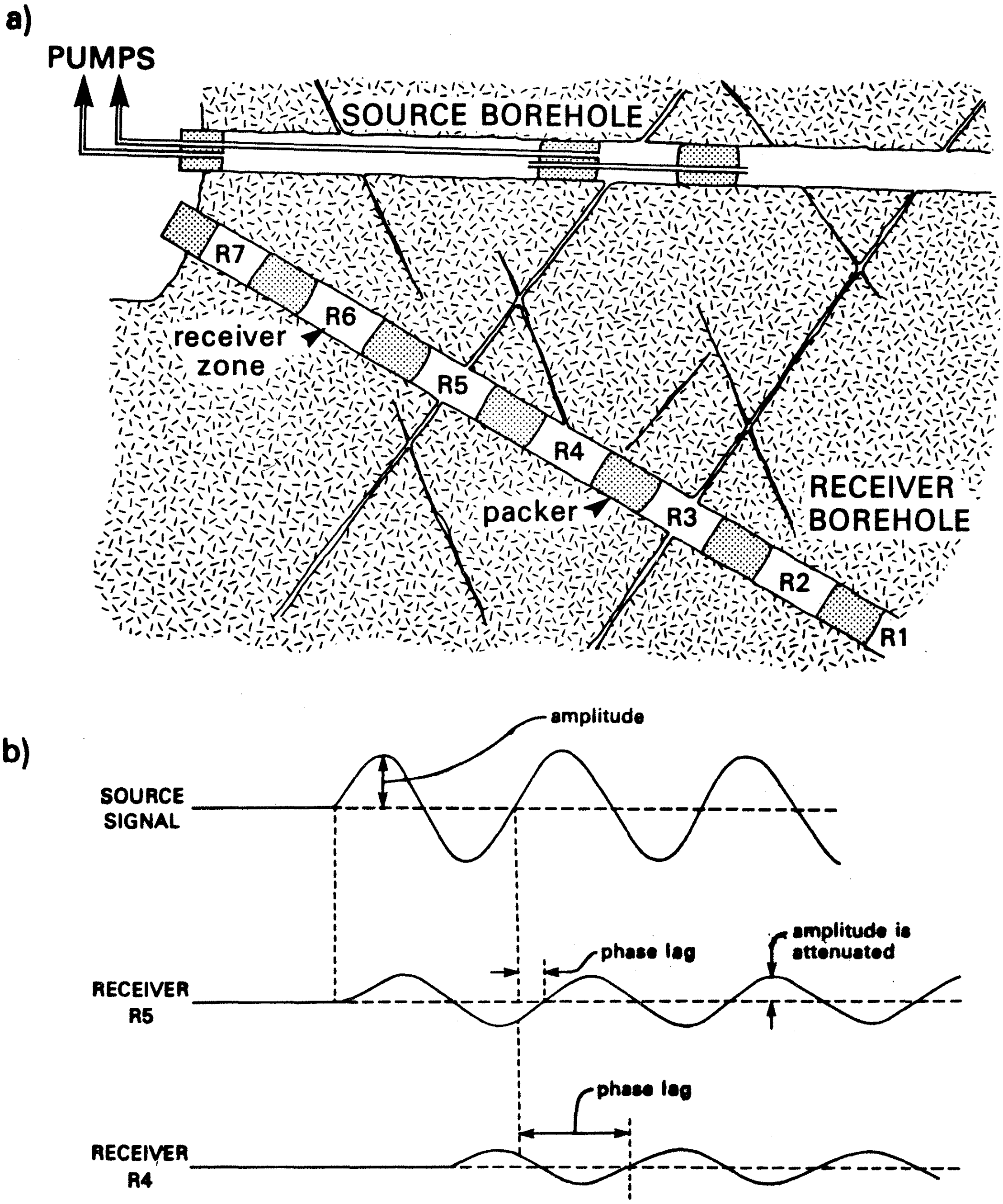


Figure 2.3 Schematic representation of a) source and receiver borehole arrangement
b) amplitude attenuation and phase lag

Disadvantages:

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. This was later extended to fissured rock in particular by Black and others, (1986). In the meantime some field experiments using slightly distorted manually-produced sinusoids had been carried out (Black and others, 1985). The interpretation of the test is effectively based again on the transient approach and yields values of K and S_s. 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.

2.4 EQUIPMENT

2.4.1 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, 1985) 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 the boreholes containing packer strings at their mouths.

The computer-controlled hydraulic testing system which was designed by B.G.S. and S.G.A.B. and built by S.G.A.B. is described in detail by Holmes and Sehlstedt, (1987). A brief summary is included below. It 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 aquisition.

2.4.2 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

2.4.2.1 Source borehole

The source borehole (Figure 2.3a) contains two hydraulically inflated packers, separated by a variable length of tubing to produce a test zone which is from 1 to 20 metres long. A rod string is used to position these and connects the source zone, between the packers, to pumps which inject or abstract water to create any required variation in pressure (called the hydraulic signal). The source zone pressure is monitored by a 35 Bar (350 m of water head) transducer located down-hole, 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 to form 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 losing pressure by water draining into the drift. The manifold is removed to re-locate either packer assembly, but can be refitted within 10 minutes. All the boreholes are sealed by plates during testing and their pressures monitored by 35 Bar transducers.

2.4.2.2 Source borehole control board

The pressures in the source borehole are controlled by a pair of pumps which are connected to the source borehole by a system of steel flow pipes, solenoid-operated valves, a control panel and a flow meter. Except for the pumps, these are mounted on a large board some 1.5 m. long and 1 m. high. The lay-out is designed in a logical manner to show the function of each flow path so that fault finding is simplified. Three flow paths are represented on the board. Firstly, there is the path from the mine water supply to the pumps. Secondly, the path for the source zone pump to the borehole and, thirdly, the path from the "rest of borehole" pump to the borehole. Each flow path contains in-line filters to extract particulate matter of greater than 0.1 µm in order to avoid damaging the pumps and solenoid-operated valves.

All the solenoid-operated valves are rated to 40 Bars and require a 220 volt power supply. The central control system provides a 24 volt signal to relays housed, together with their power supply, in the board control panel. Each valve is also connected to a display lamp in a pictogram which shows all the flow routes and the status of the valves. The valves are designed to operate efficiently in one direction. Therefore, two back-to-back valves are used in locations where flow can be in both directions.

The flow meter is a "mass flow" type and can measure from 0.05 to 1 litre/minute to an accuracy of 0.4%. At lower flows the accuracy is slightly reduced. It produces a 0 to 5 volt analogue signal which is proportional to flow but independent of flow direction. The meter is mounted on the board with associated solenoid-actuated valves so that it can be isolated from the source section flow stream when not required.

2.4.2.3 Receiver borehole

The receiver borehole (Figure 2.3a) contains six hydraulically inflated packers which isolate five short and two long zones. Each of these is connected to the instrument drift by a plastic water filled pressure tube. The packer assembly is positioned by a "blank rod string" using a hydraulically powered handling device. All the tubes emerge from the borehole through a tapered sealing manifold, similar to the one on the source borehole, and continue to the "receiver borehole control board".

2.4.2.4 Receiver borehole control 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 column of water in this tube, which has a free upper surface, can be varied in height 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 35 Bar (~350 m. water equivalent pressure) instrument can resolve to 0.1 metres with an accuracy (non-linearity and hysteresis) of +/-0.2m.. However, these values are 0.01 m. and 0.04 m. for the 7 Bar and 0.001 m. and 0.006 m. for the 1 Bar differential transducers. The reference pressure allows this accuracy to be maintained over a 0 to 35 Bar absolute pressure range. The differential transducers are easily damaged by excess pressure and need to be protected from connection to extremely different pressures.

Reading the pressure of each receiver zone follows an identical pattern, controlled by the main computer. Firstly the back-to-back solenoid-actuated valves for a particular zone are opened to connect that zone to the absolute transducer. This pressure value is then compared to a pressure reading obtained from the reference tube. If they lie within 7 Bars, the 7 Bar differential transducer is switched into the measuring loop. Normally both differential transducers are isolated from the measuring loop and the pressure is balanced across the measuring head. If the pressure difference is less than 1 Bar, the 1 Bar differential instrument can be read. This process is repeated for each preselected zone pressure until a scan of all the zones has been completed.

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.

2.4.2.5 Pumps

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 the leakage of the signal to the rest-of-borehole zone. Both pumps are, however, identically constructed. Each comprises a finely machined cylinder with a tightly fitting double-acting ram. This water pump is moved by a direct-coupled, hydraulic-augmented mechanical driving ram, the exact linear position of which is controlled by a stepping motor. Solenoid operated valves are fittted to the entrance and exit ports of the water cylinder to control the direction of flow, either into the borehole or to a storage reservoir. One step of the motor is 0.033 cm^3 of water. The flow rate ranges between 0.033 and 3000 cm^3/minute at up to 40 Bars, at which a pressure relief valve operates to protect the system against overpressurisation.

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 motor stepping rate is recorded by the control computer as a direct measure of flow rate, assuming there is no leakage around the water ram. To date only very small leakage rates have been detected.

2.4.2.6 The central control micro-computer

The key element in testing is the ability of the control system to generate the hydraulic signal in the source zone. The central micro-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.

The control system comprises a central Z80-based microcomputer driving a group of intelligent peripherals. The pumps and transducers are operated via processor-based units responding to simple command strings. This frees the central computer from time-consuming control functions. Data are stored on floppy disc and can also be presented in "real time" on a matrix printer in graphical form. Most of the programming is in Pascal MT+ to facilitate data handling.

2.4.3 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 analyse 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 analysed 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 and others, [1986]).

3. RESULTS

3.1 INTRODUCTION

The different types of result from the hydraulic tests that were carried out have natural scales associated with them. For instance, it is clear that a measurement of hydraulic conductivity derived from a comparatively short duration single borehole test is representative of a smaller volume of rock than a longer test between boreholes. In its turn, a crosshole test is a measure of a smaller volume of rock than a simulation of the response of the regional water table to the mine opening. Perhaps paradoxically, the head distribution measured during the single borehole testing has the largest scale of all. It has to be assumed that the observed head variations represent the long-term, large-scale response of the flow system to the presence of the mine cavity. It is proposed that the measurements carried out within the Crosshole Project had the following natural scales:

hydraulic conductivity derived from single borehole tests -	small scale
properties and geometry from crosshole tests -	intermediate scale
head distribution derived from single borehole tests -	large scale

The relevance of the scale of the test to the presentation of results is that the results below are presented (as far as possible) in order of increasing scale.

3.2 SINGLE BOREHOLE TESTS

3.2.1 Constant head /flow tests

3.2.1.1 Form of data

The tests were mainly of the constant head type and were carried out by S.G.A.B. in boreholes F1 and F2. The test method (see Section 2.3.1) used a head of 100 m of water which was imposed almost immediately after inflation of the packers enclosing the test zone (see Figure 3.1a). As pointed out by Carlsson

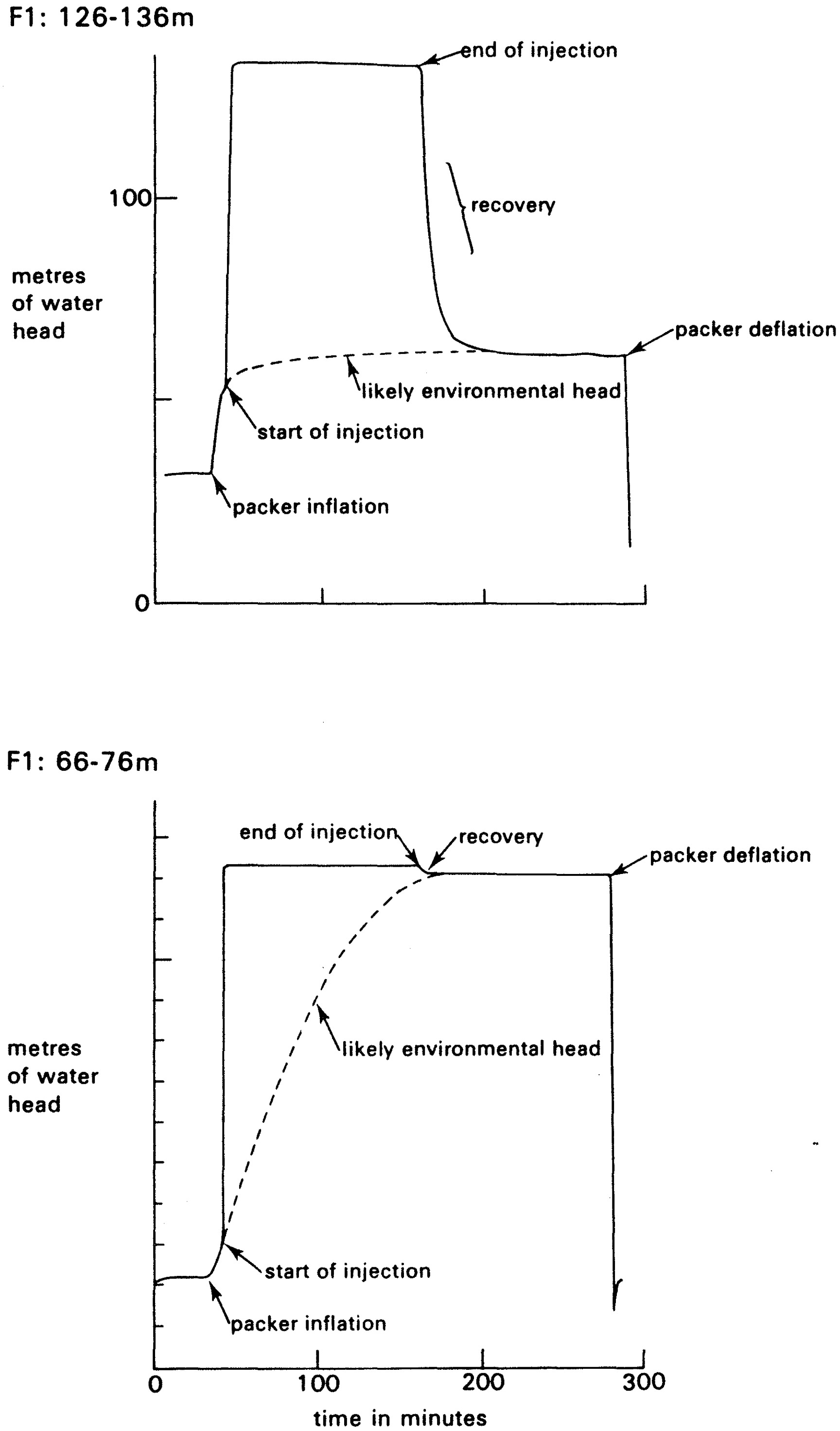


Figure 3.1 The form of data from a S.G.A.B. constant head test

a) the head fluctuations during a typical test

b) limited data from a zone with high environmental head and Olsson, (1985a), this makes no allowance for the way in which the environmental head of the zone changes during the imposition of the "constant head". This in turn has the effect of reducing the reliability of analysis methods based on the variation of inflow rate with time. In circumstances where the environmental head does not vary too greatly, then the variation with time of the manually-recorded flow rate during the injection phase of the test can be used to determine hydraulic conductivity. This is done using a "transient" formula usually based on Theis,[1935] (i.e. radial flow in an infinitely extending bounded layer).

It can be seen that the zone used in the example appears to reach a reasonably stable "environmental head" during the last 100 minutes of the test. This can be taken away from the constant head attained during the test and the resultant head difference used as the actual applied head (H_0) in a "steady state" formula.

The recovery period of the data provides another set of potential data for analysis. It has the advantage that it is unaffected by variations in the performance of the test equipment and can be used to estimate the long term environmental head in low K zones which take considerable periods to reach equilibrium.

The "good" data of Figure 3.1a should be seen together with rather "poorer" data (Figure 3.1b) where the environmental head of the tested zone was almost equal to the imposed head and hence the flow-rate based and recovery based interpretations are not appropriate.

As well as the constant head tests carried out by S.G.A.B. in F1 and F2, the bulk of F6 was tested by B.G.S. using similar methods. This was because the natural water level in borehole F6 was 40m below instrument drift level and pulse/slug tests were therefore not possible with the equipment available. In the B.G.S. testing there were both constant head tests and constant flow tests. Constant head tests were used in low K zones whilst constant flow injection tests were used in high K zones. Where zone environmental head exceeded instrument drift level (as occurred between 9 and 61m into the borehole) constant head outflow was used instead of the constant head injection tests used in the rest of the borehole. The form of the data from constant head tests in F6 was similar (see Figure 3.2a) to that from F1 and F2 except that longer periods were allowed for basic attainment of environmental head before imposition of the applied head.

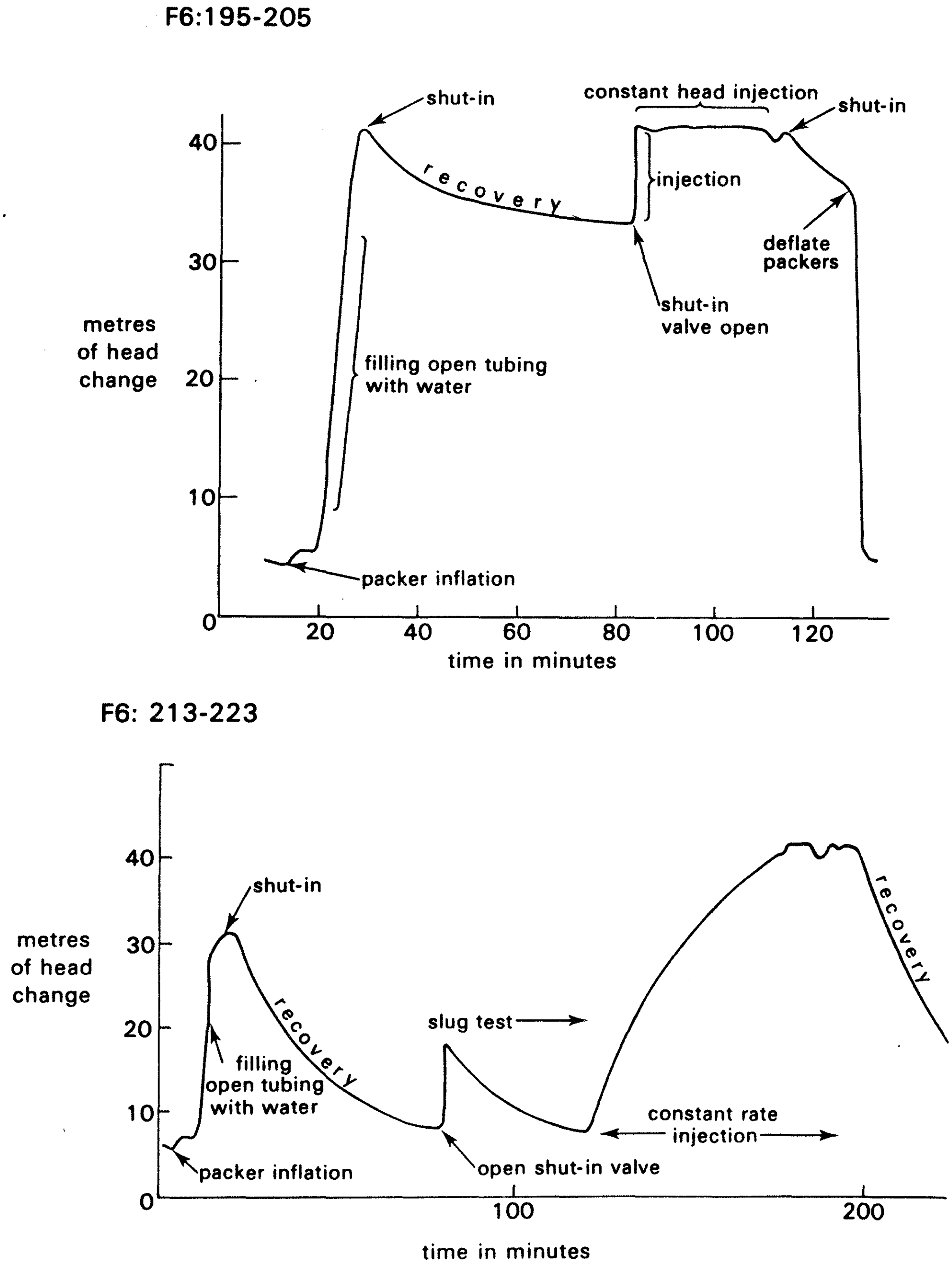


Figure 3.2 The form of data from B.G.S. "constant" type tests:
a) a constant head test b) a constant flow test.

Injection periods were shorter (40 minutes versus 120 minutes) and flow rate was recorded manually based on repeated water level drops in a small diameter tube. Monitoring of the recovery period was similar to the S.G.A.B. testing. There were only three constant flow tests, two of which consisted of injecting the mine water supply directly into the test zone via open tubing and the third involved using the computer-controlled piston pumps. A test involving the mine water supply (see Figure 3.2b) shows the form of the data. In tests of this type with low environmental heads there is a problem of filling up the tubing connecting the zone to the instrument drift. This was the reason for not using the pumps of the automated equipment as there was a good possibility of getting air-locks between the pumps and the isolated zone. One aspect which wasn't a problem in these cases was achieving a base environmental head as the zones tested in this way were all highly permeable. The data from both inflow and recovery are in these cases available for analysis using Theis based formulae.

3.2.1.2 Analysis and interpretation

The analysis of the constant head/flow tests consisted of both steady-state as well as transient approaches.

The steady-state type of analysis was applied to all of the results. The particular version of the steady state formula used throughout this programme is one attributed to Moye, (1967). Hence:

$$K = \frac{Q}{L H_0} C \qquad [3]$$

where K = hydraulic conductivity (m sec^{-1})

Q = flow rate (m^3 sec^{-1})

L = length of test interval (m)

H_0 = injection head

$$C = \frac{1 + \ln\left[\frac{L}{2r_w}\right]}{2\pi} \qquad [3a]$$

The analysis according to Moye, (1967) assumes essentially cylindrical flow from the test zone which becomes spherical at a distance of L/2 from the test zone. It also assumes that the rock surrounding the zone is a homogeneous isotropic porous medium.

The transient methods are applied to the time-dependent data as follows:

constant head tests:

injection period	reciprocal of flow versus time
recovery period	residual head versus time

constant flow tests:

injection period	head versus time
recovery period	residual head versus time

As with the steady-state formula, the analyses are based on the concept of cylindrical flow within an isotropic homogeneous porous medium. All could be described as derivatives of the basic solution of Theis, (1935). It can be seen from the table above that there are essentially 3 data sets and therefore 3 formulae. In practice the data are analysed using an approximation based on the slope of a straight line through the data when plotted versus the logarithm of time. Thus K is derived based on three versions of the basic formula:

$$K = \frac{2.3\, Q_p}{4\, \pi\, L\, \Delta h} \qquad [4]$$

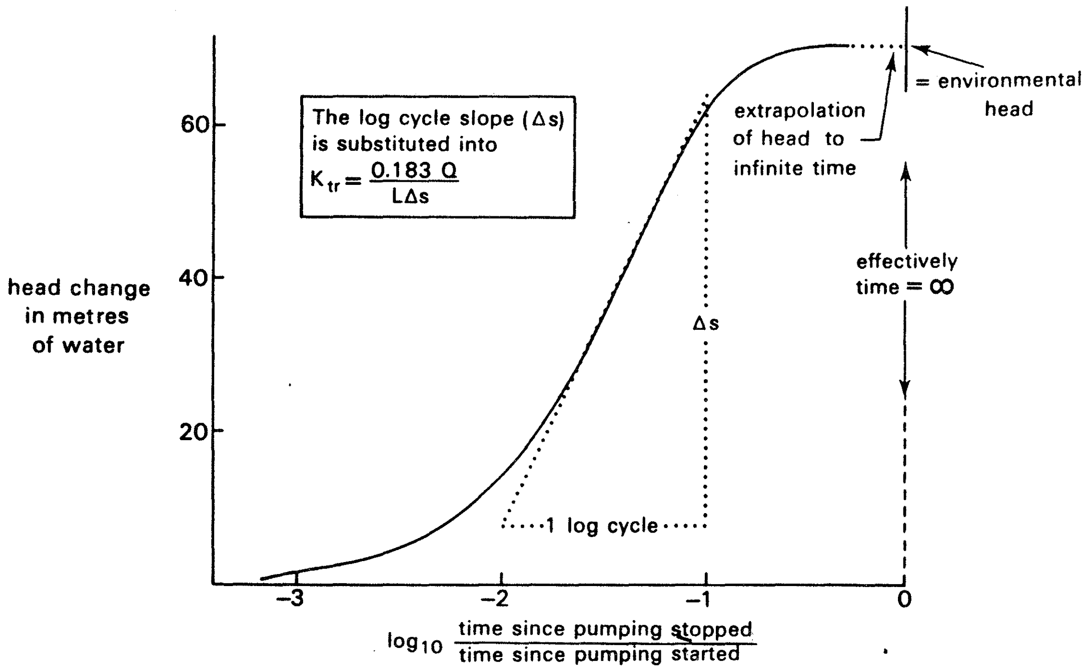
where Q_p = flow rate at end of injection period ($m^3\ sec^{-1}$)

Δh = change in head per log cycle (m)

When the recovery period is being analysed then head is plotted versus the logarithm of time since pumping stopped divided by the time since pumping started (or vice versa). The recovery period of the results in Figure 3.1a are shown in this format in Figure 3.3a. An added feature of this format is the ability to predict the long term environmental head based on the data extrapolated to infinite time (i.e. $^{t}/_{t+t'} = 1$). However there are sometimes occasions where the long term head is difficult to predict from the data available.

In cases where the variation of the flow rate is believed to be reliable then an analagous equation to equation [4] is used where $\Delta(^{1}/_{Q})$ [the change per log

F1: 126-136



F2: 46-56

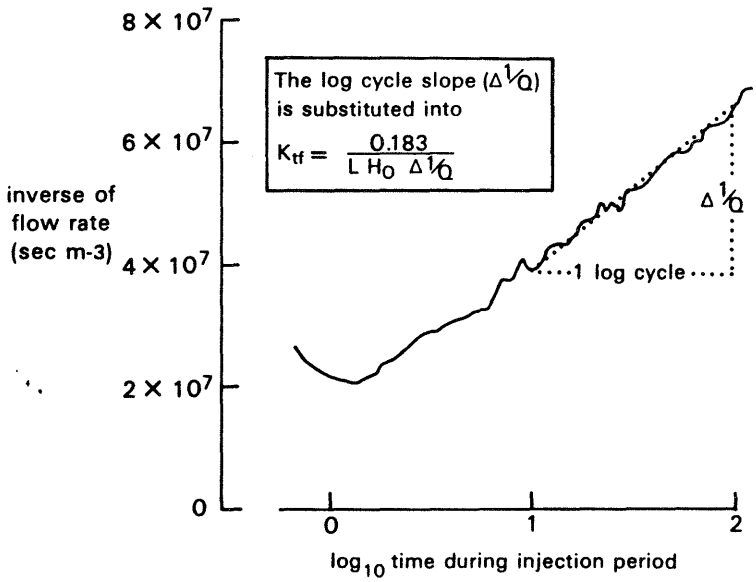


Figure 3.3 Examples of data analysis a) the recovery period of Fig. 3.1a and the extrapolation of head to infinite time. b) the injection period based on the reciprocal of flow rate.

cycle of the reciprocal of flow rate] is substituted for Δh . Additionally $^1/H_0$ is substituted for Q. An example of this type of data is given as Figure 3.3b. The results, derived by applying these approximate solutions to the basic data, are given below.

3.2.1.3 Basic results

The results of from the single borehole constant head and flow tests are given in Table 3.1. where it can be seen that there are a variable number of interpretations applied to each data set. This is because the data are of variable quality and have different errors. In some cases there were equipment problems and in others the background environmental head was a major source of drift. Some of the results however are particularly unreliable being based on limited data sets. All of them are low K zones with the exception of F2:36-46 which has an exceptionally large transmissivity. During early testing this zone gave highly confused results and was subsequently retested.

Only one zone gave results which were entirely non-analysable and this was F1:146-156. Unlike F2:36-46, this zone had a very low hydraulic conductivity. It was ascribed a value of 1×10^{-12} m sec^{-1} which seems to be the minimum value measured in other zones of these boreholes.

The results from F6 are included in Table 3.1 and it can be seen that the test intervals overlap by a metre whereas in F1 and F2 there is no overlap. This was due to practical considerations and the desire not to "miss" any permeable fractures by accident. The gaps in the results from F6 relate to low K zones where a constant head test was turned into a slug or pulse test.

Table 3-1 Results from single borehole head and flow tests

Borehole	Interval start (m)	Interval end (m)	K_{tf} (m sec^{-1})	K_{ss} (m sec^{-1})	K_{tr} (m sec^{-1})	Head* (m of water)
F1	6	16	7.6E-11			0
	16	26	3.6E-10			65
	26	36	7.1E-12			80
	36	46	1.8E-10			75
	46	56	6.1E-12			4
	56	66	2.1E-11			52
	66	76	1.0E-11			99
	76	86	6.4E-11			20
	86	96	8.4E-10			0
	96	106	1.1E-10			65
	106	116	1.8E-10			49.3
	116	126	8.3E-11			43.5
	126	136	1.1E-9			29
	136	146	1.7E-10			30
	146	156	1.0E-13			40
	156	166	2.5E-12			63
	166	176	1.1E-11			-15
	176	186	3.5E-11			45
	186	196	2.3E-11			40
F2	6	16	1.6E-12	2.3E-11	2.0E-11	49
	16	26	5.5E-12	2.9E-11	2.2E-11	65
	26	36	1.3E-11	2.0E-11	1.6E-11	37.6
	36	46	1.0E-12			0
	46	56	6.6E-12	2.6E-11		90
	56	66	1.3E-12	2.1E-11	6.2E-12	58
	66	76	2.0E-12			75
	76	86	2.0E-12			95
	86	96	2.9E-11	1.8E-10	1.1E-10	31
	96	106	2.0E-12			97
	106	116	3.0E-11	2.4E-10		60
	116	126	3.9E-9	9.3E-9	8.9E-12	48
	126	136	4.6E-11	2.8E-11	6.0E-12	14
	136	146	2.0E-12			50
	146	156	8.5E-12	1.2E-11		46
	156	166	2.0E-12			25
	166	176		1.4E-11		-13
	176	186	3.7E-11	2.3E-11	5.6E-12	-28
	186	196	1.8E-11	1.2E-11		-30
	196	206	3.9E-9	3.0E-9	5.8E-9	-1
	206	216	1.1E-9	5.2E-9	1.3E-9	12.5
	216	226	3.0E-12	7.0E-11		50
	226	236	8.3E-11	1.2E-10	8.8E-11	3.5

Table 3.1 continued

Borehole	Interval start (m)	Interval end (m)	K_{tf} ($m\ sec^{-1}$)	K_{ss} ($m\ sec^{-1}$)	K_{tr} ($m\ sec^{-1}$)	Head* (m of water)
F6[constant head]	9	19		2.1E-10		4.5
	15	25		3.2E-10		7.1
	24	34		2.0E-10		-6
	33	43		1.2E-12		23
	42	52		1.4E-11		8.2
	51	61		1.8E-12		13.5
	69	79		3.0E-10		11.4
	78	88		1.3E-11		-7.6
	87	97		1.4E-10		-7.6
	96	106		5.0E-11		-4
	105	115		3.0E-11		-5
	114	124		1.6E-9		-14.9
	123	133	1.6E-9	2.1E-9		-14.4
	132	142		1.0E-10		-7.6
	141	151	3.1E-11	2.5E-11		-7.4
	150	160	6.7E-11	1.2E-10		-7.7
	159	169	4.6E-11	1.0E-10		-8.7
	168	178		1.0E-10		-5.9
	177	187	1.1E-9	1.4E-9		-11.8
	186	196	1.1E-9	8.2E-10		-11.1
	195	205	1.9E-10	2.5E-10		-8.5
	222	232		2.8E-8		-35
	231	241		2.1E-9	2.4E-9	-37
F6[constant flow]	60	70	3.1E-9	4.5E-9		34
	204	214	4.7E-7			-40
	213	223	3.7E-8		2.6E-8	-35

* Head in metres of water relative to instrument drift

where K_{tf} = hydraulic conductivity derived from transient analysis of the injection period

K_{ss} = hydraulic conductivity derived from Moyes formula (i.e. steady state)

K_{tr} = hydraulic conductivity derived from transient analysis of recovery period

3.2.2 Pulse and slug tests

3.2.2.1 Form of data

Pulse and slug tests were primarily carried out in F3, F4, and F5 but some were also performed in the other three boreholes plus E1 to cover gaps and as part of the crosshole testing programme.

The form of pulse and slug test data is shown in Figure 3.4. The pre-test period of equilibration is particularly important in this form of testing since minor changes in environmental head can cause large distortions to the derived specific storage. In most cases the pre-test period was continued until either the rate of change of head was less than 0.01 m / minute or the rate of change was very close to being linear with time (in which case correction could be applied). Both types of test were semi-automatic in that a valve required manual opening and closing but the timing of the test and the data collection were both controlled by

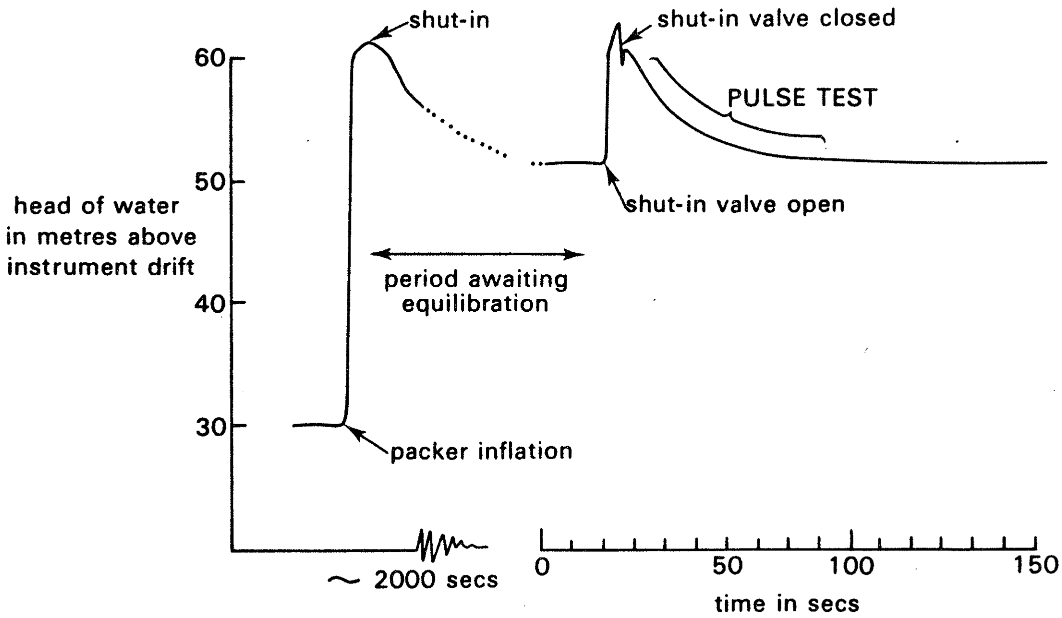


Figure 3.4 A typical pulse test from F3

the central micro-computer. Although the example in Figure 3.4 shows subsequent complete equilibration, in some low K cases the test was cut-short before this was attained.

3.2.2.2 Analysis and interpretation

After the sudden change at the beginning of a slug/pulse test, the head in the test zone returns to equilibrium approximately proportionally to the logarithm of time since the change occurred. Various versions of the same equations describe the change in head but all are essentially the ame as Cooper and others (1967), ie:

$$\frac{H}{H_0} = \frac{8\alpha}{\pi^2} \int_0^\infty e^{\frac{-\tau u^2}{\alpha}} \frac{\delta u}{u\,\Delta(u)} \qquad [3]$$

where H = head in casing at time t after sudden change

H_0 = head in casing at t = 0

$\alpha = r_{bh}^2 L\, S_s / r_e^2$ [6]

$\tau = L K t / r_e^2$ * [7]

(* nomenclature of Barker and Black, 1983; directly equivalent to ß of Cooper and others, 1967)

r_{bh} = radius of packered-off borehole

L = length of straddle

t = time since sudden change occurred

$\Delta(u) = [uJ_0(u) - 2\alpha J_1(u)]^2 + [uY_0(u) - 2\alpha Y_1(u)]^2$

This equation is not readily evaluated in the field so type curve methods are usually adopted. In the Stripa testing the data were analysed automatically using a simpler set of approximate equations. These relate the time taken to achieve some chosen amount of equilibration to the dimensionless groups α and τ. Hence:

$$t_{20\%} = (-0.135 \log_{10}[\alpha] - 0.067)\, r_e^2/LK \qquad [8]$$

$$t_{50\%} = (-0.417 \log_{10}[\alpha] + 0.07)\, r_e^2/LK \qquad [9]$$

$$t_{80\%} = (-0.48 \log_{10}[\alpha] + 0.13)\, r_e^2/LK \qquad [10]$$

where complete equilibration is represented by $t_{100\%}$.

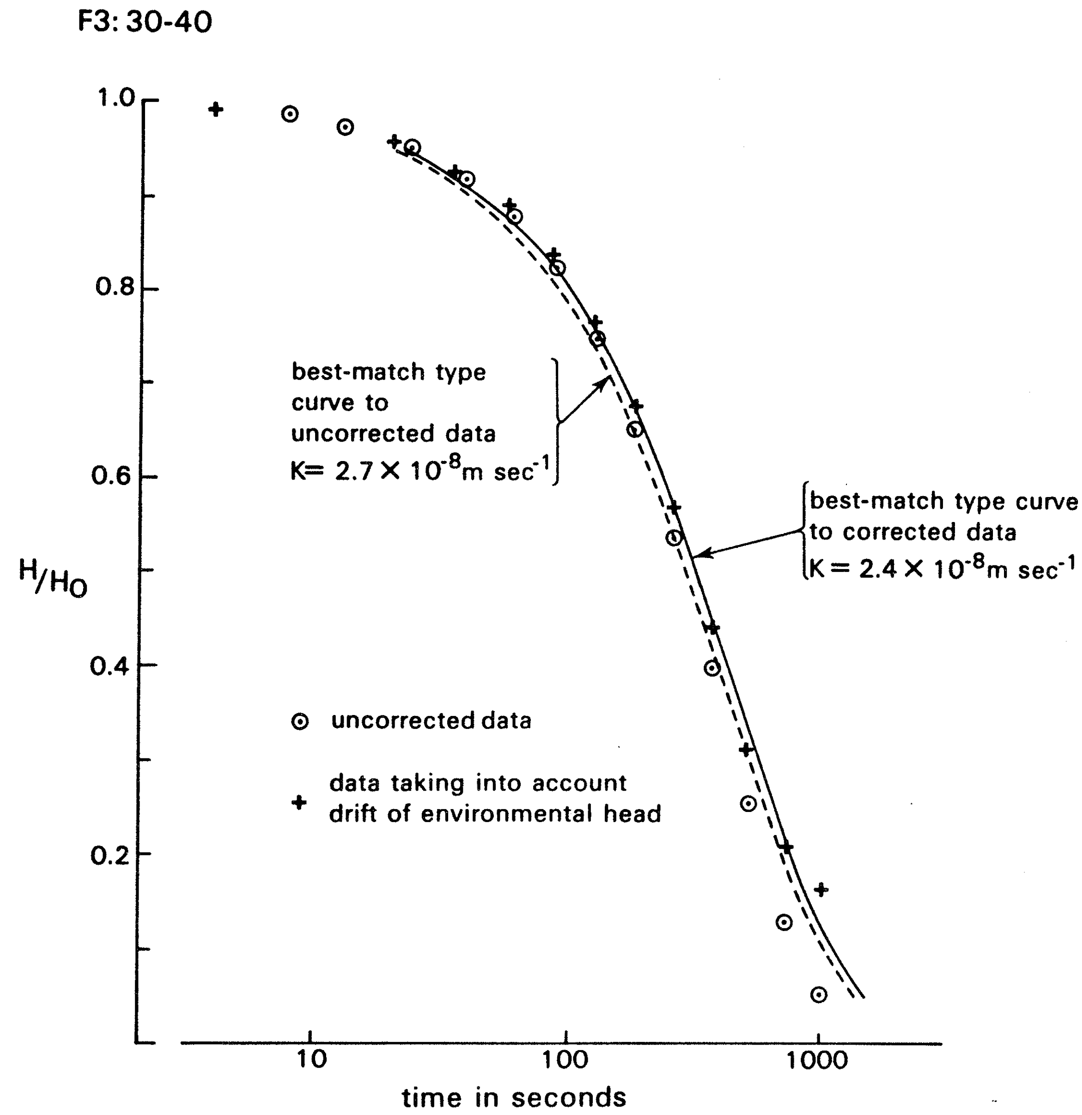


Figure 3.5 Example of slug test results with "uncorrected" and "corrected"data.

This method includes an error-minimising approach so that the effect of various corrections on the basic data can be evaluated in terms of relative error. The basic data were processed by this code, to start with, without any corrections. Next the data were "corrected" by including such factors as the drift observed during the pretest period or the drift following equilibration. At each run-through the "goodness of fit" was evaluated and the result depicted (Figure 3.5). The interpretations chosen for inclusion in the table of results were not necessarily those with the minimum error but those thought to be the "most likely". It must be borne in mind that the derived hydraulic conductivity was not particularly sensitive to this procedure unlike specific storage.

It should also be borne in mind that the analysis assumes cylindrical flow in a homogeneous isotropic porous medium. Some deviations from this assumption such as flow in fissures will be equally well interpreted using this procedure based on the type-curves of Cooper and others, (1967). Others such as skin effects will not be well interpreted.

3.2.2.3 Basic results

The results from the slug and pulse tests are given in Table 3.2. It can be seen that there are a considerable number of overlaps and duplications. In cases where a zone has been tested by both slug and pulse methods and there is a difference in the derived results then the slug test value tends to be used in later applications. This is because it is a test of a larger volume than the pulse test. Some of the analyses ran into difficulties because the data curve was outside the range of possibilities and the minimisation routine was attempting to find a solution outside the possible spectrum. In these cases the value of K was derived from the extreme value of specific storage. These results are asterisked in Table 3.2.

3.2.3 Integrated results

The programme of single borehole testing was designed to provide insights into the Crosshole Site and hence results from the different forms of test are best seen in terms of the tested boreholes. There are bound to be minor errors and inequalities involved in amalgamating tests of different type but these are felt to be of secondary importance. The results are presented below in terms of the boreholes at the Crosshole Site.

Table 3-2 Results from pulse and slug tests

Borehole	Interval start (m)	end (m)	r_e# (mm)	K ($m\ sec^{-1}$)	S_s (m^{-1})	Head* (m of water)
F1	87.45	91.45	0.62	5.2E-10	9.0E-7	13.6
	90.45	94.45	0.62	1.6E-9	2.3E-16	12.6
	93.45	97.45	0.63	6.1E-10	9.3E-6	18.5
	129.45	133.45	0.67	2.5E-10	2.8E-5	14.8
	132.45	136.45	0.68	5.2E-10	7.3E-8	37.1
F2	44	48	0.57	7.7E-8	1.3E-18	22.5
	115	119	0.66	1.9E-11	4.1E-7	33
	118	122	0.66	4.3E-8	1.3E-9	45
F3	0	13	0.5	5.2E-10	1.9E-11	42
	* 10	23	3.5	8.8E-9	6.0E-25	42
	20	33	0.53	1.1E-10	5.4E-9	39
	* 30	43	3.5	2.7E-8	6.0E-25	35
	* 40	53	3.5	2.8E-8	6.0E-25	35
	* 50	63	0.57	1.9E-9	1.6E-26	34
	* 50	63	3.5	1.2E-9	6.0E-25	3
	* 50	63	0.5	4.7E-10	7.7E-24	34
	* 55	68	0.57	3.4E-9	1.6E-26	40.3
	60	73	0.58	2.9E-10	1.6E-10	34.6
	70	83	0.6	1.3E-10	4.4E-10	37
	70	83	0.6	1.5E-10	4.4E-11	37
	80	93	0.63	7.7E-11	1.2E-7	38.8
	90	103	0.68	7.6E-11	1.4E-6	36.2
	90	103	0.68	1.6E-10	2.3E-7	36.2
	* 110	123	3.5	2.4E-8	6.0E-25	41.1
	120	133	0.66	8.1E-12	1.3E-7	42.2
	130	143	0.69	1.4E-10	3.7E-9	32.3
	140	153	0.7	2.2E-11	2.4E-8	40.1
	140	153	0.7	2.3E-13	9.5E-6	40.1
	150	163	0.7	1.4E-11	9.5E-8	15.1
	160	173	0.75	4.5E-10	1.7E-6	28
	160	173	0.75	1.1E-9	6.9E-8	28
	170	183	3.5	3.1E-10	1.5E-6	55.8
	170	183	0.75	7.9E-10	1.7E-6	55.8
	180	193	0.74	3.8E-10	6.9E-8	54.9
	183	196	0.75	5.0E-12	6.9E-6	54.9
F4	5	15	3.5	8.6E-12	5.6E-6	14
	10	20	0.51	1.9E-10	1.6E-8	31
	19	29	0.53	3.2E-11	1.8E-6	30
	28	38	0.55	7.5E-12	1.9E-9	18
	37	47	0.56	6.9E-12	1.9E-8	25
	* 46	56	3.5	3.4E-8	6.0E-24	42
	55	65	3.5	2.0E-10	6.3E-8	40
	64	74	3.5	9.3E-11	6.3E-14	46
	73	83	0.6	1.2E-11	2.2E-6	23
	82	92	0.62	4.9E-11	2.4E-7	39

Table 3-2 continued

Borehole	Interval start (m)	end (m)	r_e# (mm)	K (m sec^{-1})	S_s (m^{-1})	Head* (m of water)
	91	101	0.63	5.7E-12	2.5E-6	21
	100	110	0.64	7.1E-11	1.1E-7	11
	109	119	0.65	6.5E-11	1.9E-7	11
	118	128	0.66	1.7E-9	1.9E-7	15
	* 118	128	3.5	9.3E-9	1.3E-24	15
	127	137	0.67	1.5E-10	3.1E-5	7
	127	137	3.5	2.5E-9	6.9E-7	7
	136	146	3.5	1.0E-10	6.2E-7	7
	145	155	0.69	3.3E-11	5.3E-7	25
	154	164	0.7	2.4E-11	3.4E-7	8
	163	173	0.71	5.0E-11	3.5E-7	36
	172	182	0.72	5.5E-12	3.6E-7	6
	181	191	0.72	1.0E-11	3.3E-9	9
	190	200	0.73	1.2E-10	3.7E-11	23.6
	199	209	0.75	8.8E-11	3.5E-9	-1
	208	218	0.76	4.6E-12	3.8E-7	14
	217	227	0.77	2.5E-10	6.8E-7	4
	236	246	0.79	1.8E-10	5.3E-9	5
F5	10	20	3.5	4.8E-8	2.8E-17	13
	19	29	0.53	4.7E-11	1.9E-9	36
	28	38	0.56	5.3E-10	1.2E-23	36
	37	47	0.57	7.8E-9	2.8E-20	37
	46	56	0.58	2.7E-9	5.4E-17	43
	55	65	0.6	5.4E-11	2.2E-7	42
	64	74	0.61	1.2E-11	2.3E-7	44
	73	83	0.62	8.4E-11	6.2E-7	40
	82	92	0.615	1.4E-12	2.6E-5	35
	91	101	0.625	5.1E-10	1.7E-7	30
	91	101	3.5	5.E-9	2.1E-9	30
	100	110	0.64	1.6E-10	1.1E-5	31
	100	110	3.5	5.2E-11	8.5E-6	31
	109	119	0.65	5.3E-12	7.4E-6	29
	118	128	0.66	1.2E-12	1.9E-5	31
	127	137	0.67	4.4E-9	7.8E-10	12
	127	137	3.5	1.8E-9	5.4E-12	12
	136	146	0.68	6.5E-10	8.0E-9	35
	136	146	3.5	7.5E-11	8.5E-7	35
	145	155	0.69	6.8E-12	1.3E-5	40
	154	164	0.71	3.94E-10	8.8E-6	32
	154	164	3.5	6.6E-11	5.4E-5	32
	163	173	0.71	3.88E-11	5.5E-7	30
	172	182	0.73	2.83E-9	9.0E-9	30
	172	182	3.5	3.5E-10	3.4E-6	26
	181	191	0.73	2.35E-9	5.9E-6	57
	181	191	3.5	3.52E-10	2.1E-5	57
	186	196	0.74	1.18E-9	1.5E-5	62

Table 3-2 continued

Borehole	Interval start (m)	Interval end (m)	r_e# (mm)	K ($m\ sec^{-1}$)	S_s (m^{-1})	Head* (m of water)
F6	69	79	0.6	3.0E-10	6.0E-7	11.4
	213	223	21	2.6E-8	5.7E-9	-35
	231	241	21	2.4E-9	3.3E-6	-37

r_e is effective radius in mm. N.B. Values less than 1mm indicate pulse tests
* head in metres of water relative to instrument drift

3.2.3.1 Distribution of hydraulic conductivity

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

Table 3-3 Hydraulic conductivities of the boreholes

borehole	hydraulic conductivity ($m\ sec^{-1}$) average	mean
Fl	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 the table above and Figure 3.6, the boreholes are comparatively similar in their average properties. Borehole Fl in the north of the site is the least

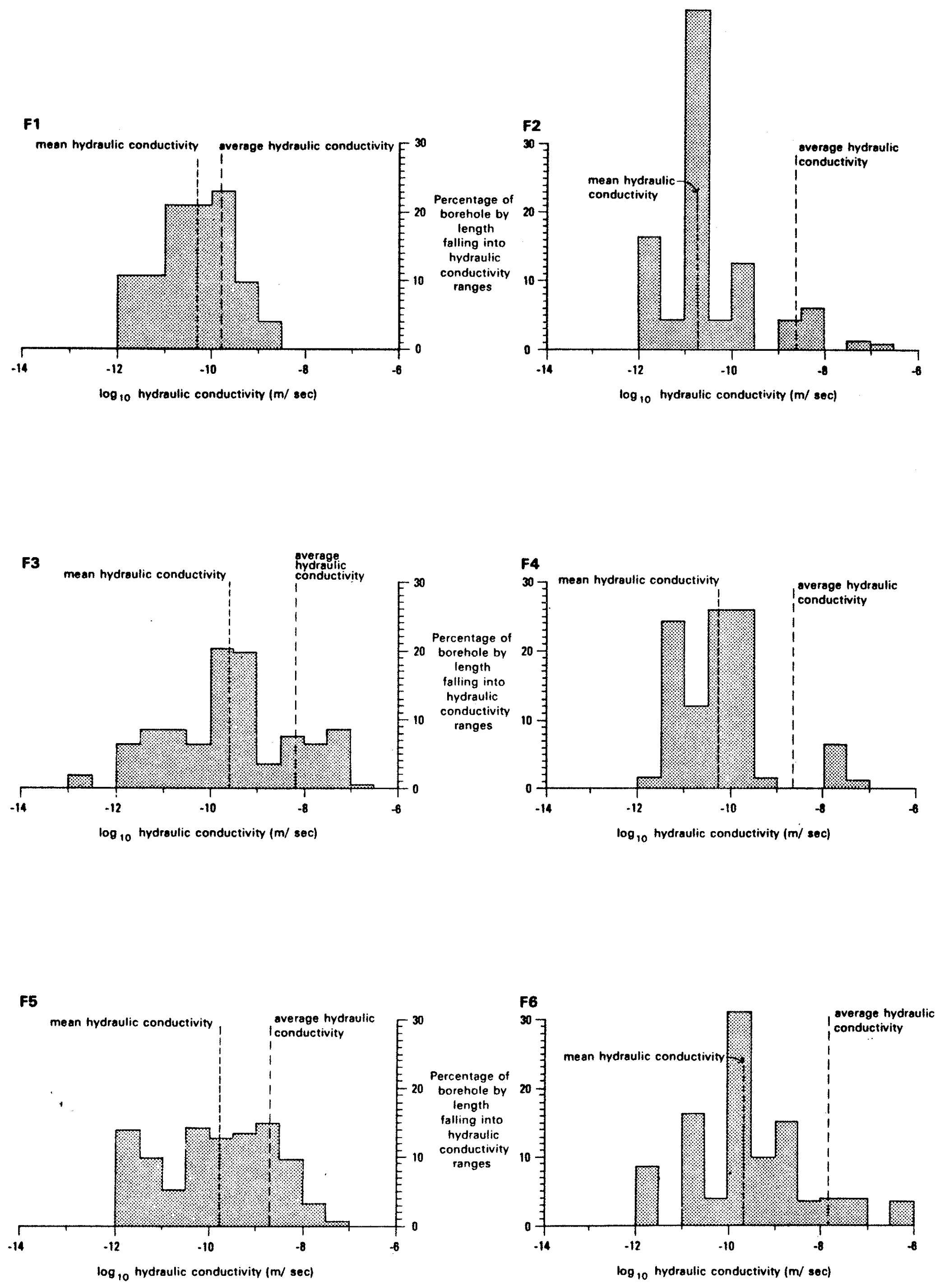


Figure 3.6 Hydraulic conductivity distributions for the six boreholes of the Crosshole Site

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 andf 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 K borehole, contains no identifiable permeable zones, and hence has mean and average K differing by only half an order of magnitude. The other boreholes are intermediate between these extremes. The frequency distribution of the combined results (Figure 3.7) shows the distinct cut-off, close to the measurement limit at a hydraulic conductivity value of 1 x10^{-12} m sec^{-1}. The distribution is slightly skewed towards lower values but this may be due to the lower K 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.

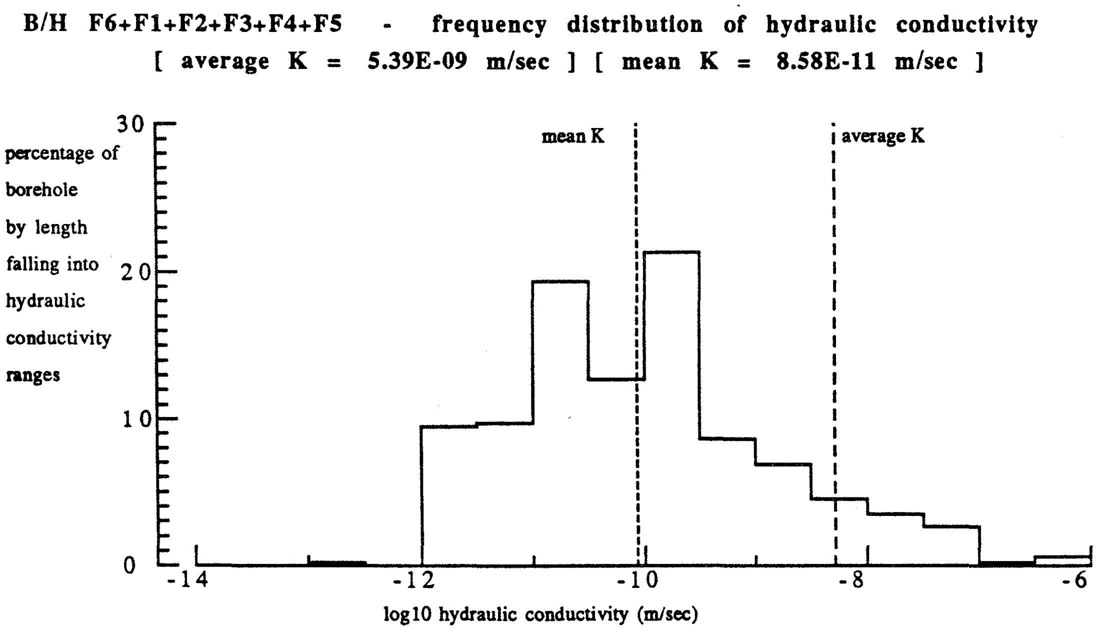


Figure 3.7 The frequency distribution of the combined hydraulic conductivity results

3.2.3.2 Overlapping tests and hydraulic conductivity profiles

As can be seen in the tables of results (Tables 3.1 and 3.2) tests vary in straddle length and many overlap. In these cirumstances, it becomes a problem to produce a profile of the hydraulic conductivity variation down the length of the borehole. A "sifting" system has been devised to overcome this problem and has been written in the form of a microcomputer code known as "KSIFT".

The aim of the programme is to reduce a series of overlapping tests to a single continuous histogram. The basic idea of the sifting programme is to "sift upwards" aiming to reduce the eventual lengths of highly permeable intervals. Hence where a series of tests overlap (Figure 3.8) first of all the lowest values are picked. Where these overlap more permeable tests, it is assumed that the low permeability of the low permeability zone is equally distributed along its entire length. Hence the low K of the low K zone is assumed to apply in part of the higher K zone. In order for the test on the higher K zone to be true then the rest of the higher K zone must have a raised K in order to maintain the same measured transmissivity. Hence higher K zones which are overlapped by lower K zones are "squeezed" and raised. (see Figure 3.8).

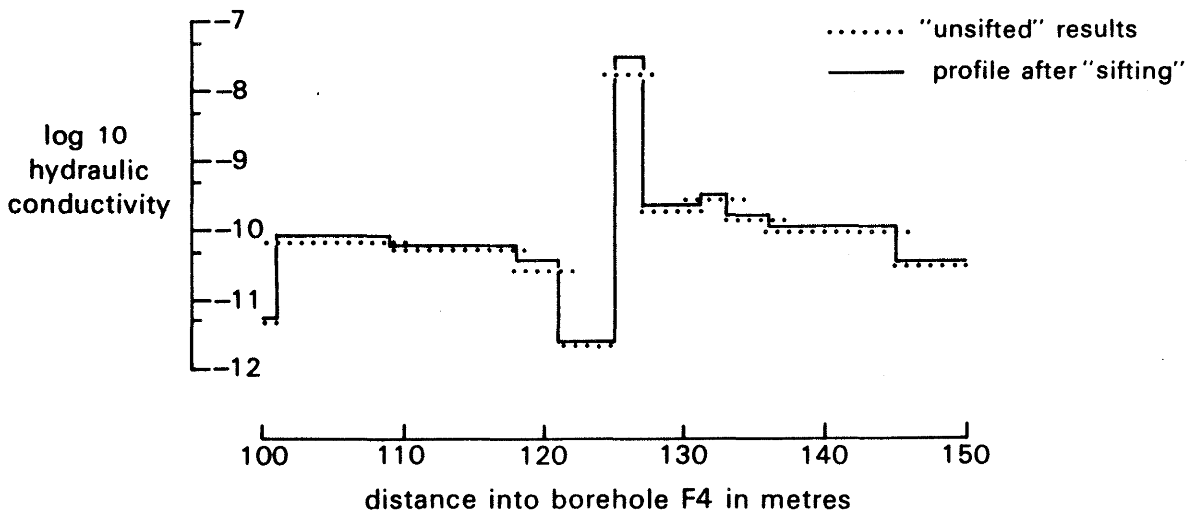


Figure 3.8 "Sifting" of overlapping results: a section of F4 before and after "sifting".

Alternative strategies for sifting could have been chosen, such as reducing the K of the non-overlapped portion of the low K test or giving the overlap region an intermediate value. The system involving squeezing high K zones was preferred because it was not likely to produce ridiculously low values of K and narrow zones of high K are the most appropriate concept in a fissured rock. Had the rock been a porous medium without fissures, the intermediate strategy would have been chosen. There are still, however, occasions when values from different tests are incompatible and in the "KSIFT" code the operator is asked to choose which test to ignore or alter. Where the tests were repeated in the same interval and yielded different results, then in general, the tests with the larger radius of influence were used as input to the "KSIFT" procedure.

The result of applying this "sifting" procedure to all of the boreholes is shown in Figure 3.9. It can be seen in Figure 3.9 that there is no consistent variation in K along the boreholes. The high K zones are generally better defined into narrower than average intervals because of the extra, short-straddle testing which took place. This was focussed on the high K zones for the purposes of cross hole testing.

3.2.3.3. Distribution of head

The environmental head was measured at the same time as the hydrualic conductivity. When the results were "sifted" the head measured in a particular interval was retained even if the interval was reduced in length or even bisected. Only in one of the six boreholes did there seem to be a relationship between head and hydraulic conductivity. This was F6 (see Figure 3.10a) but the relationship was mainly due to the high K zone of very low head between 205 and 231m. All the other boreholes had apparently random spreads of data. However, when all the tests are taken together (see Figure 3.10b) some broad relationships are apparent. Firstly high hydraulic conductivity is never associated with high head and secondly low K is never associated with low head.

The variation of head is considered in more detail in Section 3.4. below.

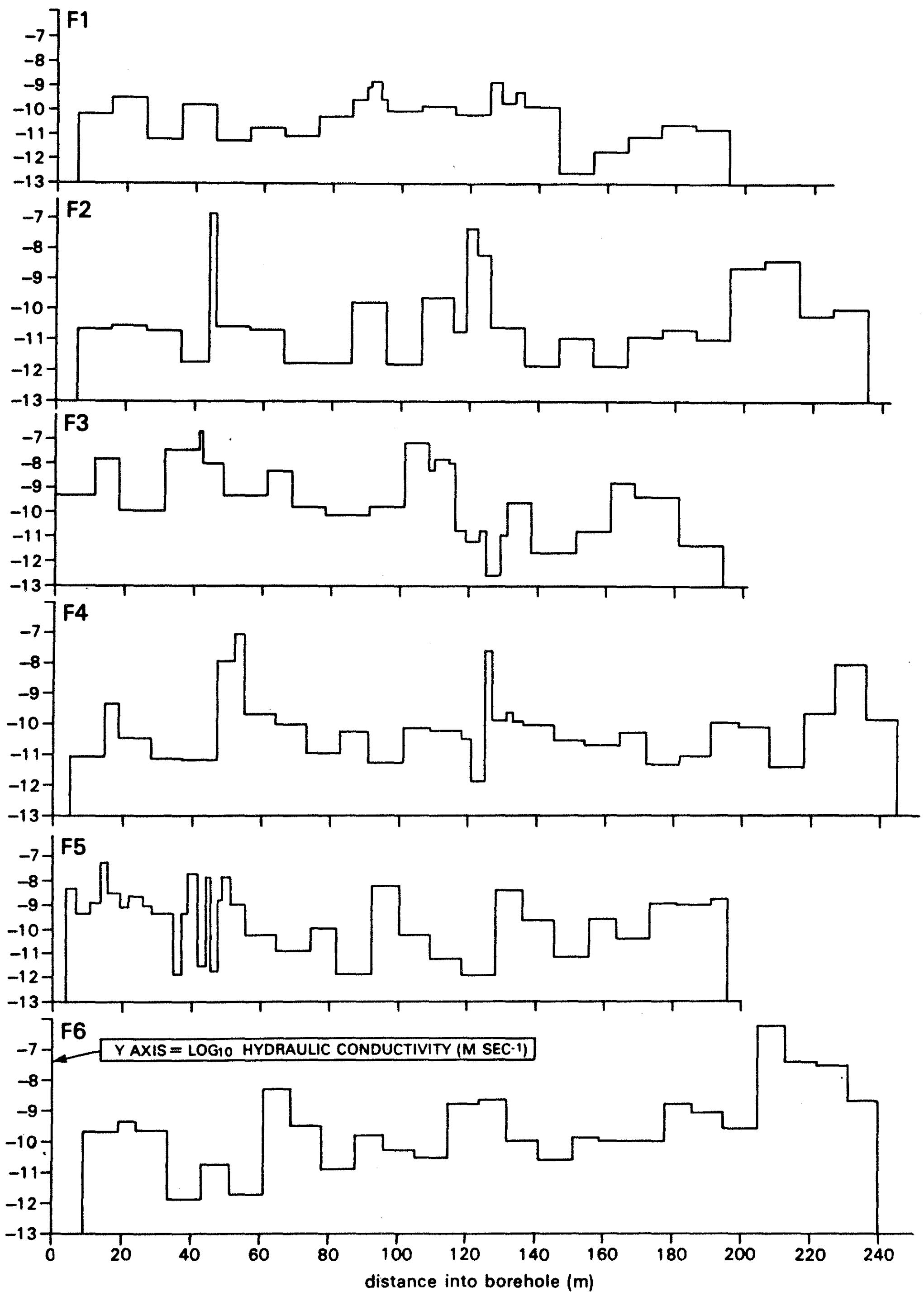
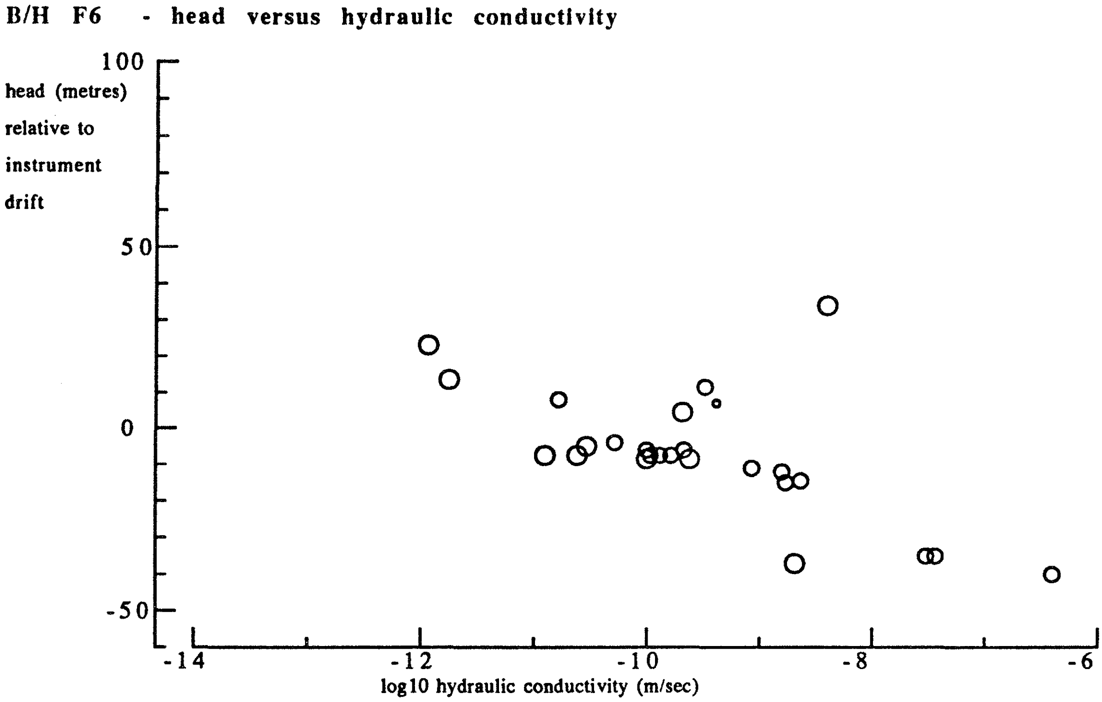


Figure 3.9 The distribution of hydraulic conductivity in the boreholes of the Crosshole Site.



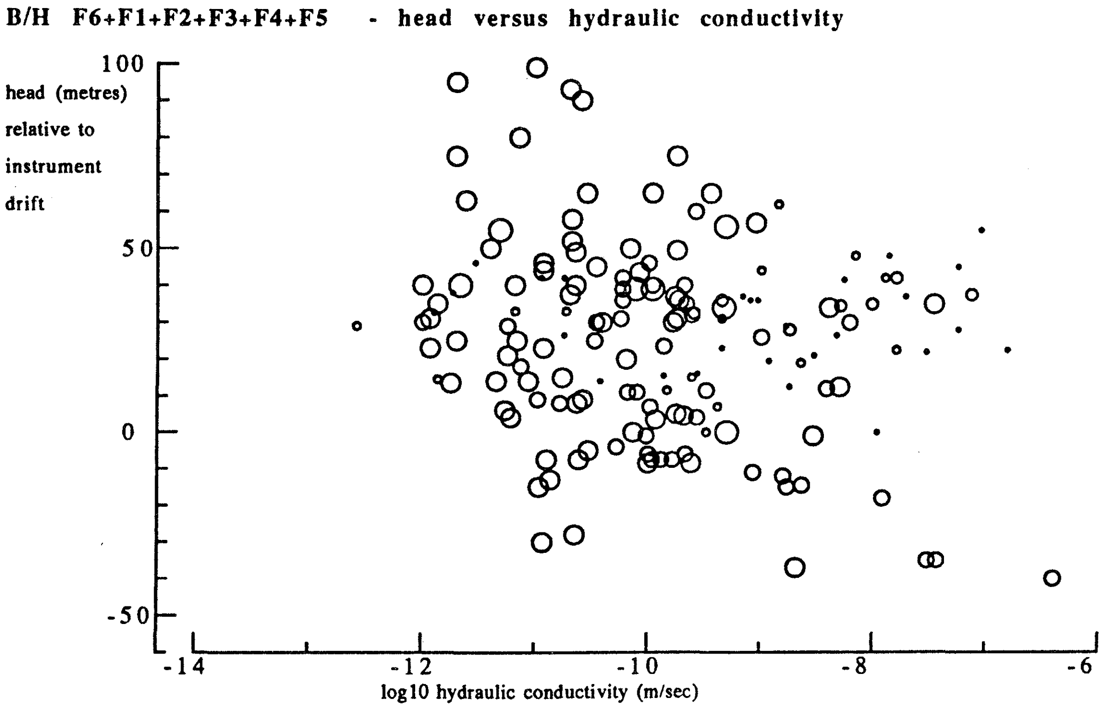


Figure 3.10 The relationship between head and hydraulic conductivity a)Borehole F6 b)all boreholes (NB the size of circle is proportional to the length of zone)

3.2.3.4 The relationship between derived hydraulic conductivity and specific storage

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 as either a "large-storage" porous medium or a "low-storage" fissure.

The first parameters which need to be established are the likely properties of the matrix and the possible occurrence of unfissured rock. It is evident that unfissured granite could be expected to have a low matrix hydraulic conductivity (K_m) and a reasonably large specific storage (S_{sm}). The results (Tables 3.1 and 3.2) show that the lowest measured values of K are around $1x10^{-12}$ m sec^{-1} (excluding a value of $2.3x10^{-13}$ m sec^{-1} measured in F3) with associated S_s values of between $1x10^{-6}$ m^{-1} and $1x10^{-4}$ m^{-1}. The 19 tests containing values of this type amount to a total of 143m out of the 1282m which were tested. Most of these tests were 10 m long so unfractured rock is quite common. The borehole F2 appears to be unfractured over about 20% of its length (when measured by 10 long tests). These values are in line with K measurements determined in granite by other experiments (i.e. Brace, 1980, Katsube, 1982)

If the results are considered as a whole then certain relationships should be apparent from the derived values of K and S depending on whether the rock is behaving as a fissured porous medium or a homogeneous porous medium. This approach is more reliable when applied to a group of results rather than an individual result owing to the likely inclusion of results containing a wide variety of possible errors. The relationships are based on the concept of slug (or pulse) tests with cylindrical flow in a homogeneous and a fissured porous medium (see Figure 3.11). If the tests were all of the same straddle length, effective radius and the granite had consistent matrix properties then the result could be expected to fall into narrower "bands".

The results derived from the testing of boreholes F3, F4 and F5 (see Figure 3.11) appear to broadly indicate a response from a fissured porous medium. There are however, a broad group of results with high specific storage (i.e. 1 x 10^{-6} - 1 x 10^{-4} m^{-1} and mid range K ie 1 x 10^{-10} - 1 x 10^{-8}m sec^{-1}) which do not

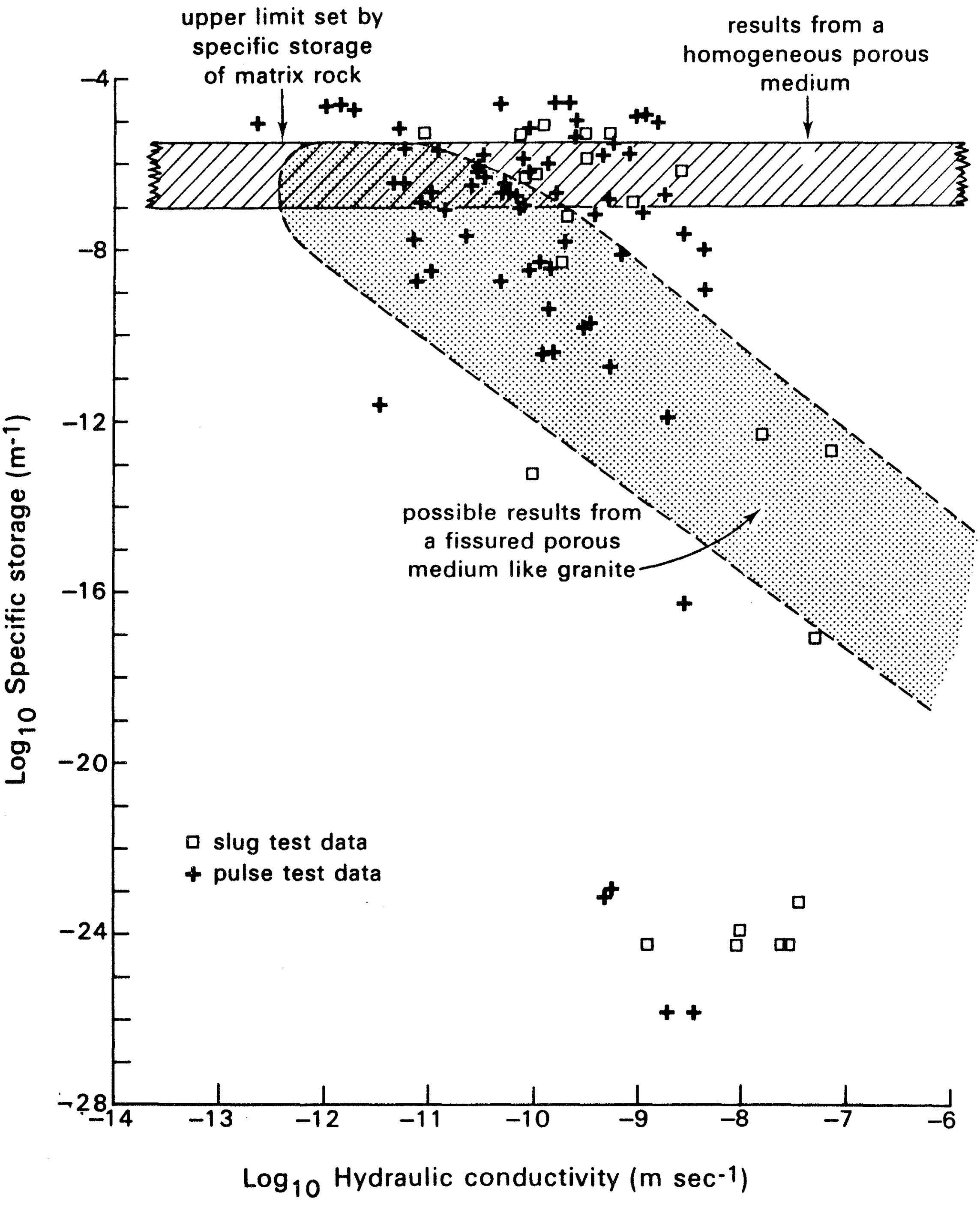


Figure 3.11 Slug and pulse test derived values of K and S_s from boreholes F3, F4 and F5 together with fields of expected results based on differing flow concepts.

agree very well with the fissured porous medium interpretation. Another aspect of this group of results is the very high derived values of specific storage. This is contained in both slug and pulse test results. In normal circumstances matrix granite would be expected to have a specific storage value between 5 x $10^{-6}m^{-1}$ and 1 x $10^{-7}m^{-1}$. From Figure 3.11 it appears that about 20% of the results lie above this upper limit. Another group of results which deserve attention are those with derived values of specific storage less that 1 x $10^{-20}m^{-1}$. It was shown by Black (1985) that low values of specific storage would be derived by applying standard homogeneous porous medium based analysis to fissured porous media. However it is not possible to derive values less than about 1 x $10^{-20}m^{-1}$ even in the most extreme cases. These results therefore must arise from another source of interpretation error. The most likely candidate is skin effect with a positive skin which, in some circumstances (particularly pulse tests), would cause a deviation in the response. This deviation would increase the steepness of the data curve resulting in the data being matched by type curves with very low α values (and hence low derived S_s). An alternative cause of the excessive steepness of the data curve might result from a changing environmental head during the test. This though would usually affect long duration tests most whilst the data is mostly of the highest K values which are the tests of shortest duration. A second alternative cause could be over-correction by the interpreter of the test. However, since the values are excessively low, interpreters would tend to correct the data to yield more likely values of S_s.

A data curve from this group is shown in Figure 3.12 which exhibits the form expected with positive skin (positive skin is where a region in the immediate vicinity of the borehole has a lower K than the rest of the rocks). With positive skin the equilibration is slow at first and effectively speeds up (relative to that which would be expected of a homogeneous porous medium). Given that positive skin is present in some tests negative skin might also be expected. The tests with high S_s have therefore been examined and an example typical of negative skin is shown as Figure 3.12b. It is very much in line with the response expected by Moench and Hsieh, (1984) exhibiting the break of slope as the hydraulic signal penetrates the skin.

The work by Black, (1985) showed that repeated tests with the same characteristics in rock with the same matrix properties should result in a

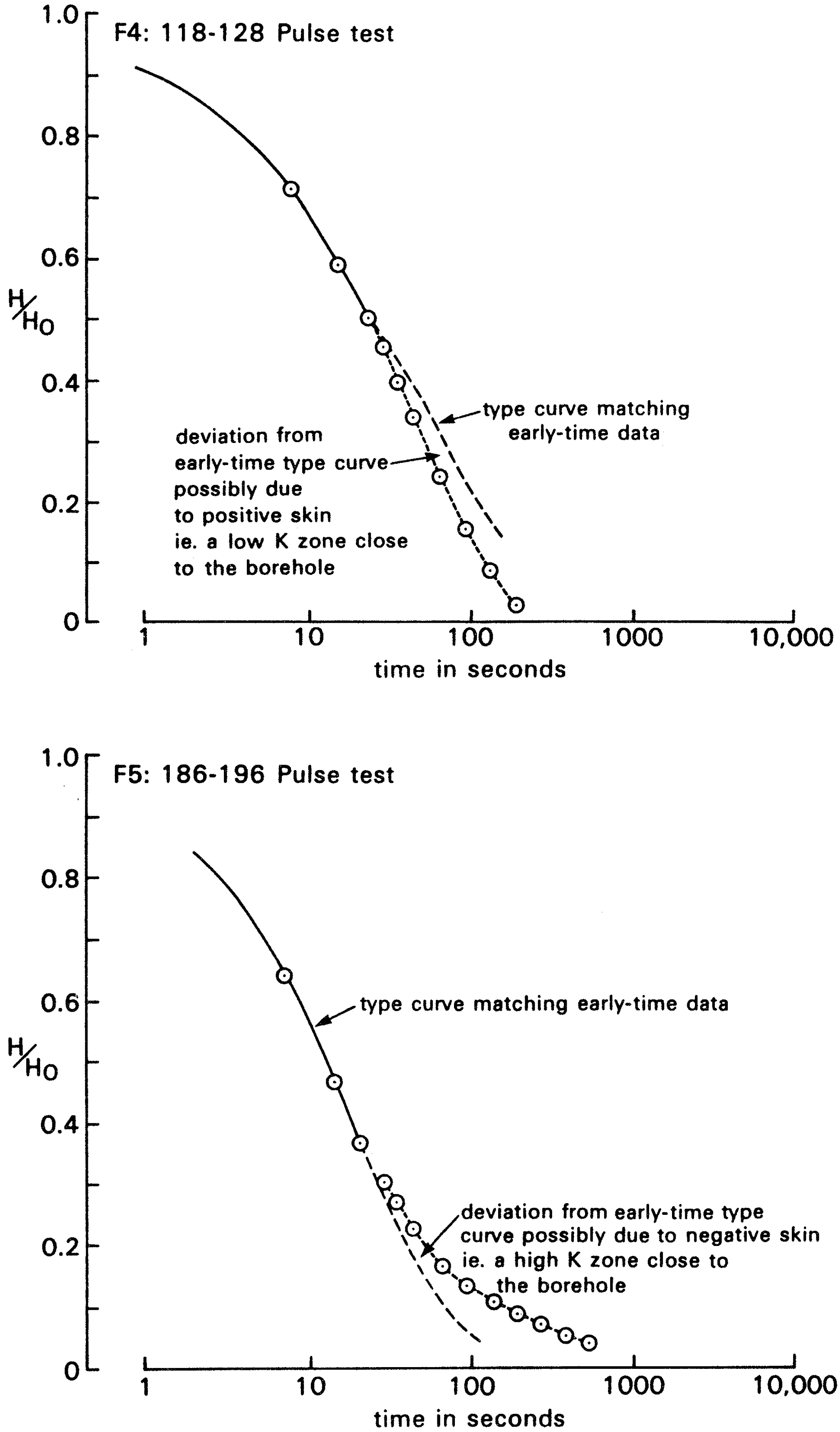


Figure 3.12 Data curves showing skin effect a)positive skin b) negative skin

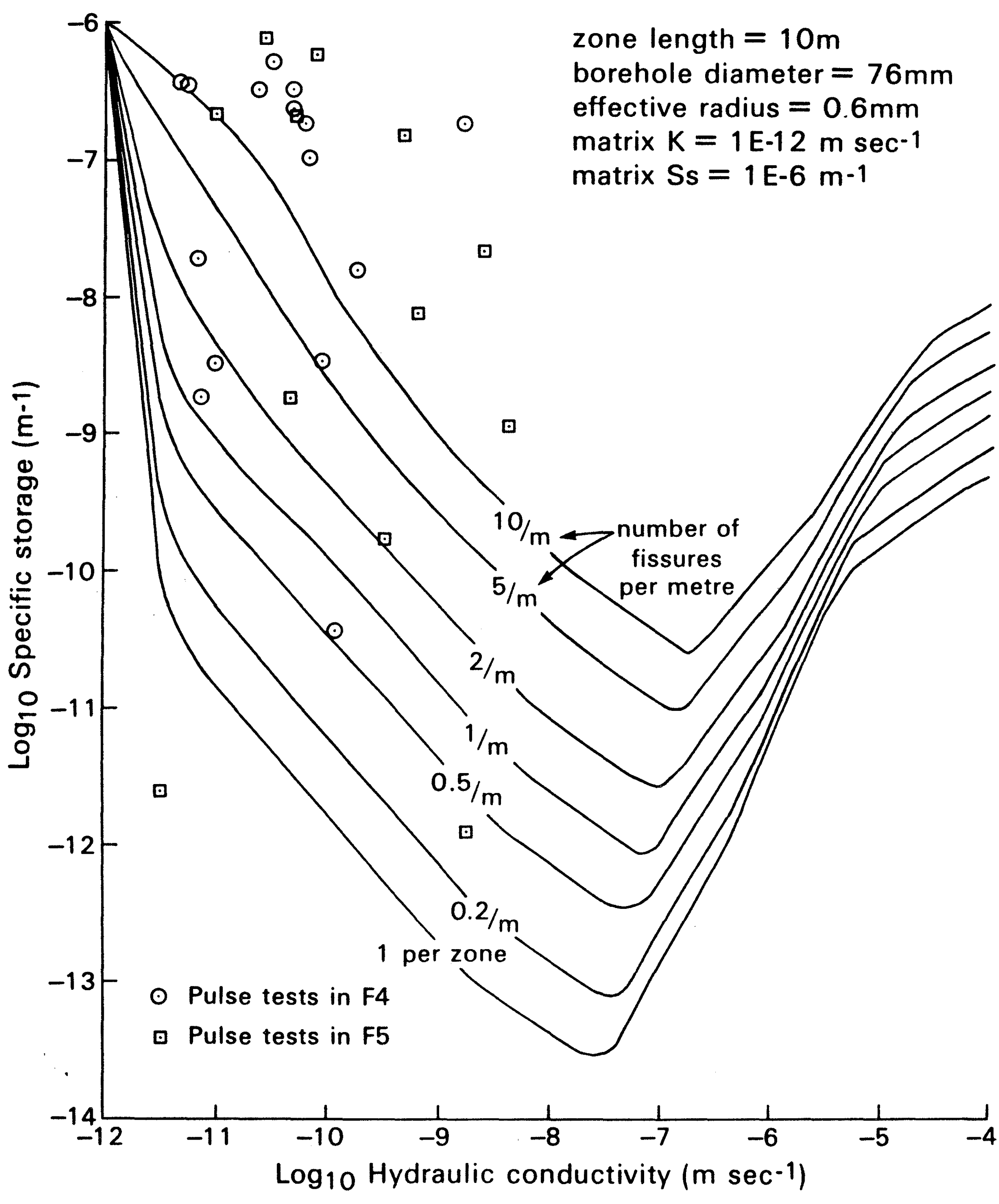


Figure 3.13 The derived K and S_s of pulse tests from F4 and F5 compared to the predicted response of a test with the indicated characteristics.

predictable series of possible responses. By assuming that the two matrix properties of the rock (K_m and S_{sm}) are approximately known and that the flow in the fissures obeys the "cubic law" (i.e. the transmissivity of a plane parallel fracture is proportional to its aperture cubed), then the derived values of K and S_s are dependent on the number of fissures taking part in the test. The tests can only be compared together if they have similar straddle lengths and effective radii. This reduces the size of the groups for comparison.

For the purposes of this comparison the matrix properties have been assumed to be 1×10^{-12} m sec^{-1} for K_m and 1×10^{-6} m^{-1} for S_{sm}. The pulse test data from F4 and F5 have been examined in this way and the results (see Figure 3.13) are somewhat representative of the result achieved with the data from other boreholes for different tests. The common feature they show is that there are few results in the range 1×10^{-12} m sec^{-1} to 1×10^{-11} m sec^{-1} and the results in this range do not have the expected high values of storage. The most disturbing aspect of this form of examination is the apparently large number of results implying that there are more than 10 hydraulically active fractures per metre in the test zone. There appear to be no tests where a 10m straddle zone has included only one active fracture. In addition there are a number of results with specific storages larger than 1×10^{-6} m^{-1} which did not plot on the diagram. Given that there are apparently such frequent fractures then shorter straddle intervals are more likely to result in tests which contain only one fracture. Therefore the 4m long slug tests from F4 have been plotted in the same way as the 10m pulse tests from F4 and F5 above (see Figure 3.14). The difference between the previous representation and that here is the choice of matrix K (K_m) which has been raised to 1×10^{-11} m sec^{-1}. Examination of the whole data set indicates that there are only a few results with similar derived parameters (see Figure 3.11) and that, allowing for mistakes in the data, there are not a large number of tests containing single fissures.

Hence it would appear that, whilst there are a reasonable number of tests containing unfissured matrix rock, there are only a small number of tests containing single fissures. Where these do occur, the matrix K is quite large indicating perhaps that the granite is altered when adjacent to active fractures. There are also a surprisingly large number of tests which seem to be yielding porous medium responses (ie responses with a high specific storage around

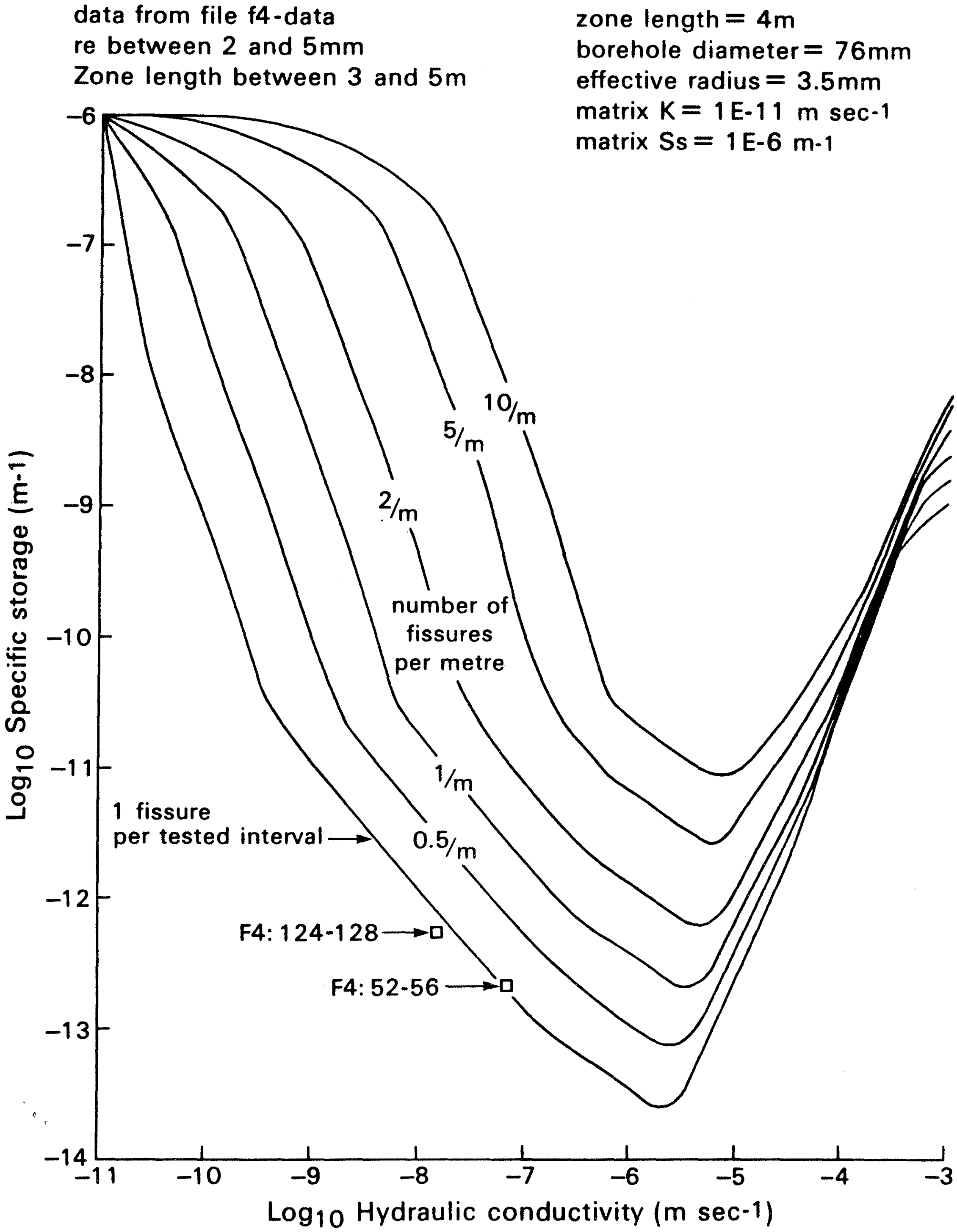


Figure 3.14 The derived K and S_s of two slug tests in 4m straddles in F4 indicating single fissure response.

$1 x 10^{-6} m^{-1}$). Alternatively there are a large number of tests containing very frequent fractures. It should be emphasised that these considerations on fractured responses assume that fractures are plane parallel-sided features which (in single hole testing) contain strictly radial flow.

3.3 CROSSHOLE TESTS

The crosshole testing was performed after the completion of the single borehole testing. Given the length of the boreholes within the fan-array, a "tomography type" approach was clearly impossible. It would have been comparatively easy to pump each one of the boreholes in turn and measure the response of the other complete boreholes. However this would not have yielded any information about the particular between-borehole flow paths or where they intersected the boreholes. The procedure adopted was to test in the region of broad zones identified by the geophysical techniques (see Olsson and others, 1987). Whilst testing in the vicinity of these zones, the rest of the borehole and its neighbours was monitored for evidence of the source zone signal. Hence it was hoped to identify all significant crosshole connections in addition to those selected on the grounds of geophysics.

The major facet of the crosshole testing was the use of the sinusoidal method of testing.

3.3.1 Sinusoidal tests

The sinusoidal method is a novel form of hydrogeological testing and hence has a limited literature concerning analysis and interpretation. Thus the detail of the analysis and interpretation of the sinusoidal tests carried out within this programme is reported separately by Noy and others, 1987. The description below represents a practical summary.

3.3.1.1 Form of data

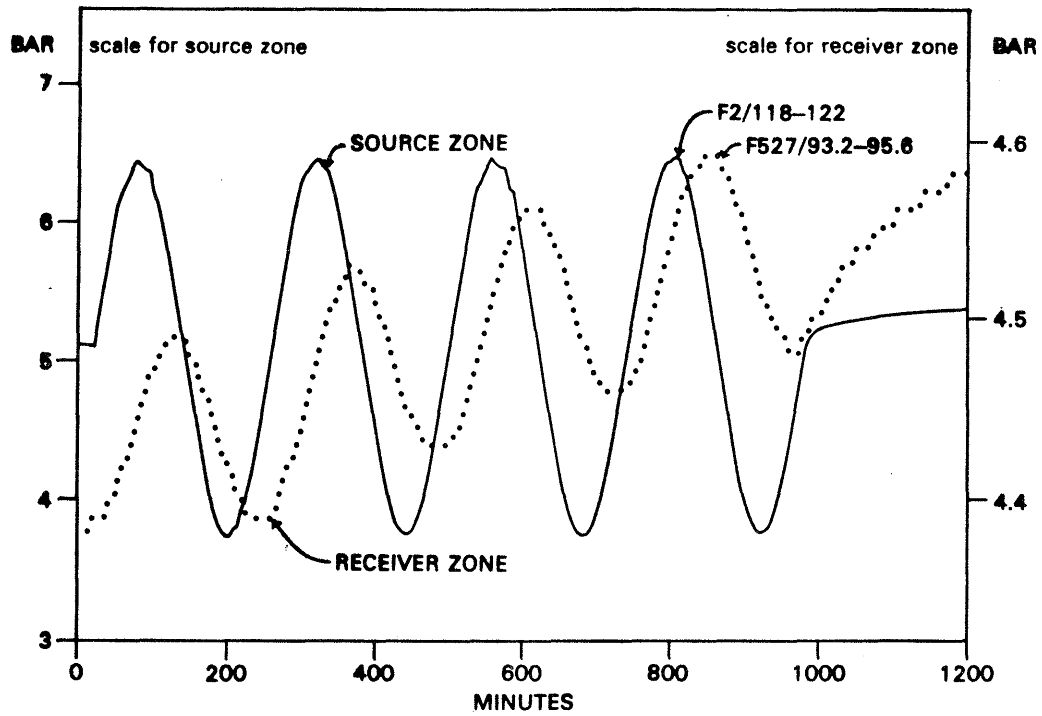
Sinusoidal tests were run by computer once the operator had set the two strings of packers and measurement equipment in the chosen position in the boreholes and supplied the necessary information. The source string always contained a 4m long straddle-packered zone to delimit the source with the remainder of the borehole connected together via a tube through the source zone. The packers were each 1.15 m long. The receiver zone contained six 1.15 m long packers separated by 2.4m long straddles. The end-zones of the receiver string were not connected together. The operator defined the test in terms of whether it was a sinusoidal variation of flow or pressure, the peak amplitude of either and the period of the test.

The computer recorded the source and receiver measurements and when there were responses they were of the form shown in Figure 3.15a. This is typical data in that the received signal is imposed on a gradually changing background environmental head. In order to derive the basic parameters, amplitude attenuation and phase lag, for analysis the raw data requires correcting for drift. This was achieved using a microcomputer program called "SINEFIT" and was carried out at the mine. In essence the program applies a drift correction and then performs a least squares fit of each signal to a sinusoid of period equal to the test. It then writes out amplitudes and phase lags of the receiver data relative to the source data and plots the resultant match (see Figure 3.15b). The program is detailed in Black and others, (1986).

3.3.1.2 Basic results

The results of the sinusoidal testing are given in Table 3.4. They are divided according to the geophysically defined zone which was suspected to be present in the vicinity of the emplaced straddle intervals. The table does not include the tests which were carried out within the respective zones but which did not yield measureable results. In particular boreholes F1 and E1 were searched for responses but none was found. The borehole F6 is ommitted from the results because there was no sinusoidal testing involving F6 owing to the low heads pertaining in that borehole. This was because the sinusoidal method was centred on equal volumes of injection and abstraction. Abstraction was not possible.

a) RAW DATA



b) FITTED SINE WAVES BY "SINEFIT"

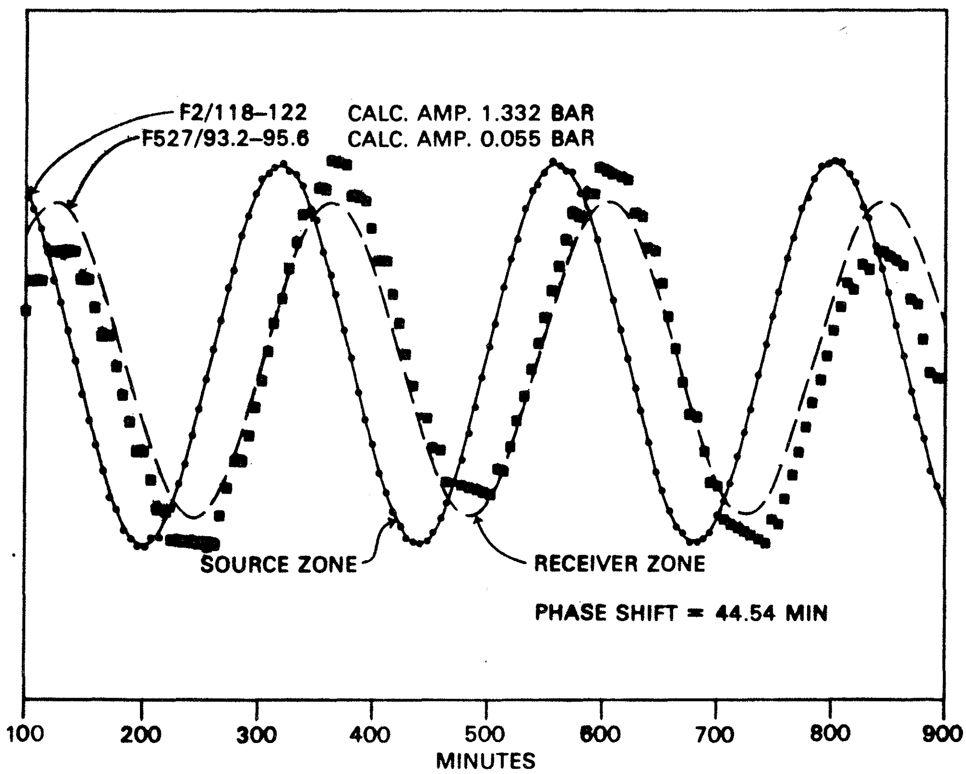


Figure 3.15 Manipulation of data to yield basic data of amplitude attenuation and phase shift
a) raw data b)fitted sine waves by "SINEFIT"

Table 3-4 Results from the sinusoidal testing

source-receiver boreholes	zone identifiers [separation] (m)	DETAILS OF SINE WAVE AT SOURCE				RECEIVED SIGNAL	
		period (minutes)	peak flow (m^3/sec) [x 10^6]	peak head (m)	flow/head phase shift (degrees)	peak head (m)	phase shift (degrees)
GEOPHYSICAL ZONE A							
4 -> 5	c - b [27]	1440	3.5	9.89	2.7	0.666	48
		240	2.5	9.94	17	0.442	73
	+++	240	3.0	10	2	0.327	40
		60	37	6.61	27	1.03	54
		10	35	3.9	31	0.269	65
	c - c [27]	1440	3.5	9.89	2.7	0.769	37
	c - d [26]	1440	3.5	9.89	2.7	0.625	49
		240	2.5	9.94	17	0.368	92
	+++	240	3.0	10	2	0.257	54
3 -> 4	b - c [23]	720	1.8	9.7	3	0.157	5
		240	1.9	9.64	3	0.087	66
		40	1.9	9.66	6	0.158	14
		10	1.9	9.72	11	0.095	39
2 -> 4	a -c [15]	480	2.0	9.74	9	5.8	15
		40	3.2	10.2	47	6.6	52
		10	7.1	12.72	52	6.5	64
	a - b [12]	480	2.0	9.74	9	4.7	34
	a - a [12]	480	2.0	9.74	9	3.67	71
3 -> 5	b - a [14]	720	1.7	9.66	11	0.23	104
	b - b [14]	720	1.7	9.66	11	1.83	51
		12	1.7	8.65	8	0.23	49
		6	1.4	9.43	20	0.099	60
	b - c [15]	720	1.7	9.66	11	0.59	101
2 -> 3	a - a [14]	720	3.3	8.95	3	0.09	20
		60	4.0	9.66	22	0.08	64
	a - b [13]	720	3.3	8.95	3	0.11	28
		60	4.0	9.66	22	0.10	56
	a - c [12]	720	3.3	8.95	3	0.036	27
		60	4.0	9.66	22	0.09	78
	a - d [12]	720	3.3	8.95	3	0.041	29
		60	4.0	9.66	22	0.09	78

Table 3.4 continued

source-receiver boreholes	zone identifiers [separation] (m)	DETAILS OF SINE WAVE AT SOURCE period (minutes)	peak flow (m^3/sec x 10^6)	peak head (m)	flow/head phase shift (degrees)	RECEIVED SIGNAL peak head (m)	phase shift (degrees)
GEOPHYSICAL ZONE C							
2 -> 5 -+-	e - e[64]	240	3.1	13.31	12.9	0.578	81.7
-+-		40	2.6	8.79	30.3	0.068	163.8
3 -> 5	e - e [36]	1440	3.9	7.28	18.6	3.05	36.1
		60	9.4	5.32	56.5	0.984	112.5
		40	18.1	5.69	59.1	0.82	138.2
		40	20.1	8.26	65.2	1.14	132.9
	g - e [41]	720	1.2	9.36	1.9	0.125	32.3
3 -> 2 ***	f - b [28]	1440	5.1	8.43	12.5	2.75	48.5
***	f - c [29]	1440	5.1	8.43	12.5	2.80	48.0
***	f - d [30]	1440	5.1	8.43	12.5	4.99	30.5
***	f - e [31]	1440	5.1	8.43	12.5	4.97	20.8
***	f - f [33]	1440	5.1	8.43	12.5	2.26	21.3
2 -> 3	e - f [31]	720	1.9	9.46	12.5	1.7	49.7
		240	2.0	9.45	16.5	1.2	61.0
		60	2.7	9.90	30.5	0.47	87.8
		15	4.5	10.76	35.5	0.17	14.6

Notes
+++ = not processed by SINEFIT due to errors in file header
-+- = probably transmitted through borehole F3
*** = test lasted less than one cycle

Positions of identified zones

zone labels	position of labelled zone in borehole (distances in m from collar) F2	F3	F4	F5
a	43.3 - 47.3	34.3 - 36.7	46.3 - 48.7	34.4 - 36.8
b	105 - 112	37.8 - 40.2	49.8 - 52.2	38.0 - 40.4
c	113 - 115	41.4 - 43.8	53.4 - 55.8	41.5 - 43.9
d	116 - 119	44.9 - 47.3		48.2 - 50.6
e	116 - 123	103 - 106		93.2 - 95.6
f	123 - 126	107 - 109		
g		110 - 116		

The testing was organised so that a 24 hour period sinusoid was carried out first followed by the shorter periods until they diminished below measurement limits. The shortest possible period using the equipment was about 2 minutes but this depended on the number of differential transducers being read and the time allowed for the transducers to settle.

As can be seen in the table there were 47 positive results including multiple tests on the same source - receiver pair. The tests were quite time-consuming mainly because it was necessary to check all borehole responses to ensure that responses were not being transmitted via other boreholes.

3.3.1.3 Qualitative interpretation

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 3.16. It can be seen that Zone A has more responses in the southern part 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.

The other zone which was extensively tested was Zone C. Since it intercepts the boreholes further from the instrument drift the distances between the boreholes are larger than applies to Zone A. However, if anything, the number of responses seems to increase towards the north rather than the opposite in Zone A.

3.3.1.4 Quantitative interpretation

There are a number of source - receiver pairs in Table 3.4 each containing a variable number of data sets at different signal frequencies. The interpretation of this complex data set is necessary in order to quantify the groundwater flow properties of the crosshole connections.

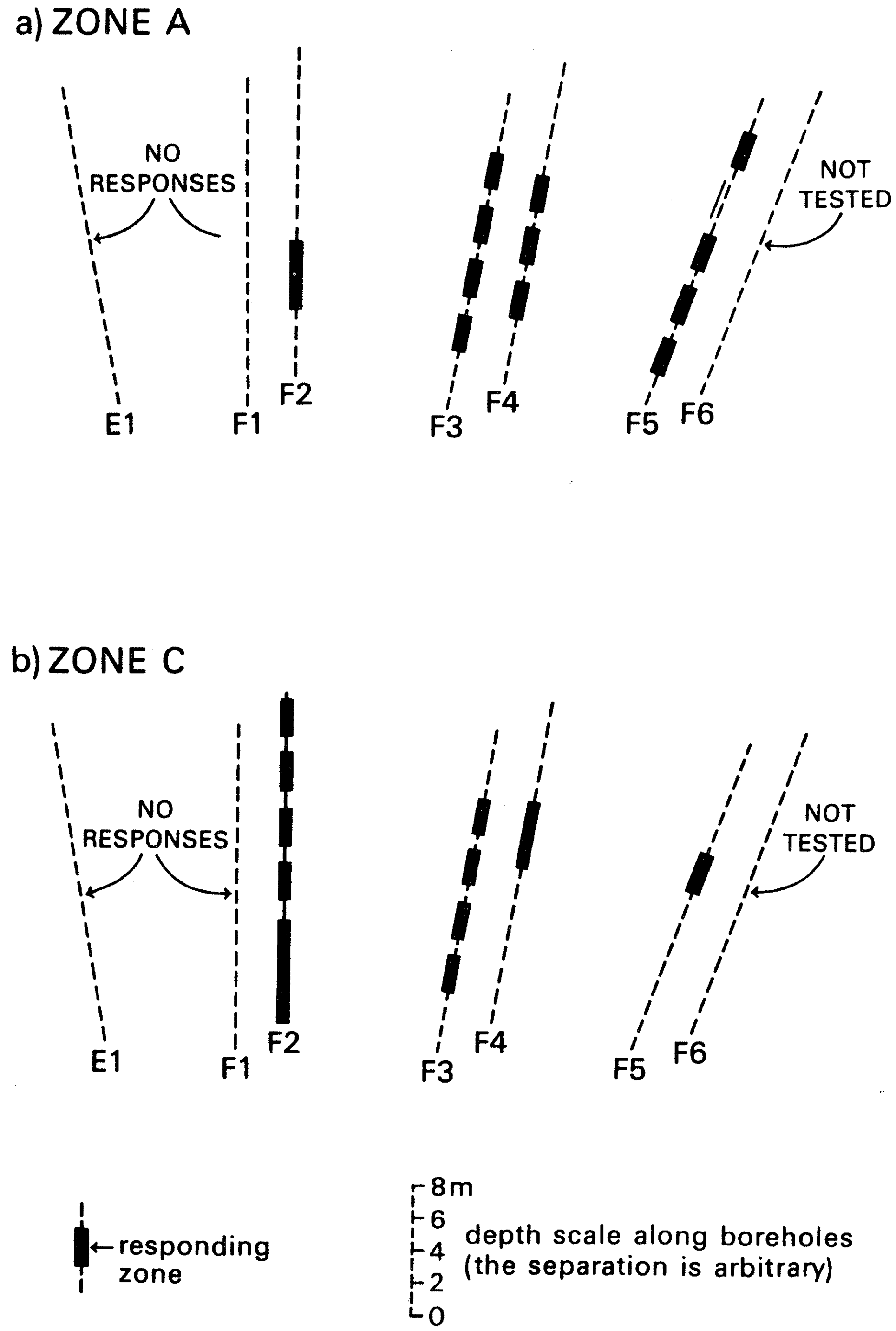


Figure 3.16 Pseudo-perspective plan of the intervals where crosshole responses were measured: a) Zone A b) Zone C

The problem of interpretation of these tests lies in the geometry of the flow system being unknown. A preliminary set of possible geometries, based on aquifer hydrogeology, was put forward in Black and others, 1986. Possible geometries 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 others, 1987).

The first step in the interpretation was to examine the data sets for consistency. This meant that if there was no consistent relationship between the amplitude and phase shift of the received signal and the 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 cause of inconsistency probably lies in different configurations of the other boreholes which did not contain the source and receiver equipment. If the borehole is shut-in then it is possible to transmit a pressure signal through it from zone to zone.

The next step in the interpretation procedure was to apply the 1-D and 2-D models to the major responses in each source/receiver data set. This was taken as the longest period test in each set. It was usually a test with a 24 hour period. The analysis procedure is based on taking the measured flow in the source zone and predicting the head and phase lag in the receiver interval. A minimisation technique (see Black and others, 1986) was used to derive the K and S_s which yielded the prediction closest to the measured values. This was carried out for both 1-D and 2-D flow concepts. 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.

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. Thus as flow expands from a single channel into a fracture plane, via channel intersections, the dimension parameter increases from 1 to 2. With increasing scale this dimension can be expected to grow to values around 3. The calculated value of the dimension parameter would therefore be expected to vary with distance between source and receiver points. The development of the fractional dimension analysis is detailed in Noy and others, (1987). The overall effect of these considerations is that the test is analysed 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 can be summarised in table form:

Table 3.5 Summary of fractional dimension interpretations

Source	Receiver	flow dimension	source amplitude measured	source amplitude predicted	source phase lag measured	source phase lag predicted
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. The next step in the development of the interpretation was to examine the other higher frequencies.

The properties and dimension for each pair were used to predict the receiver zone responses at higher frequencies based on knowing the source flow. Additionally the amplitude and phase lag of the source zone head were also predicted. 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 a zone which is more sparsely channelled. The diffusivities derived from these interpretations are given in Figure 3.17. It appears that most diffusivities 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 3.16). Zone C shows a similar trend but with the reverse orientation.

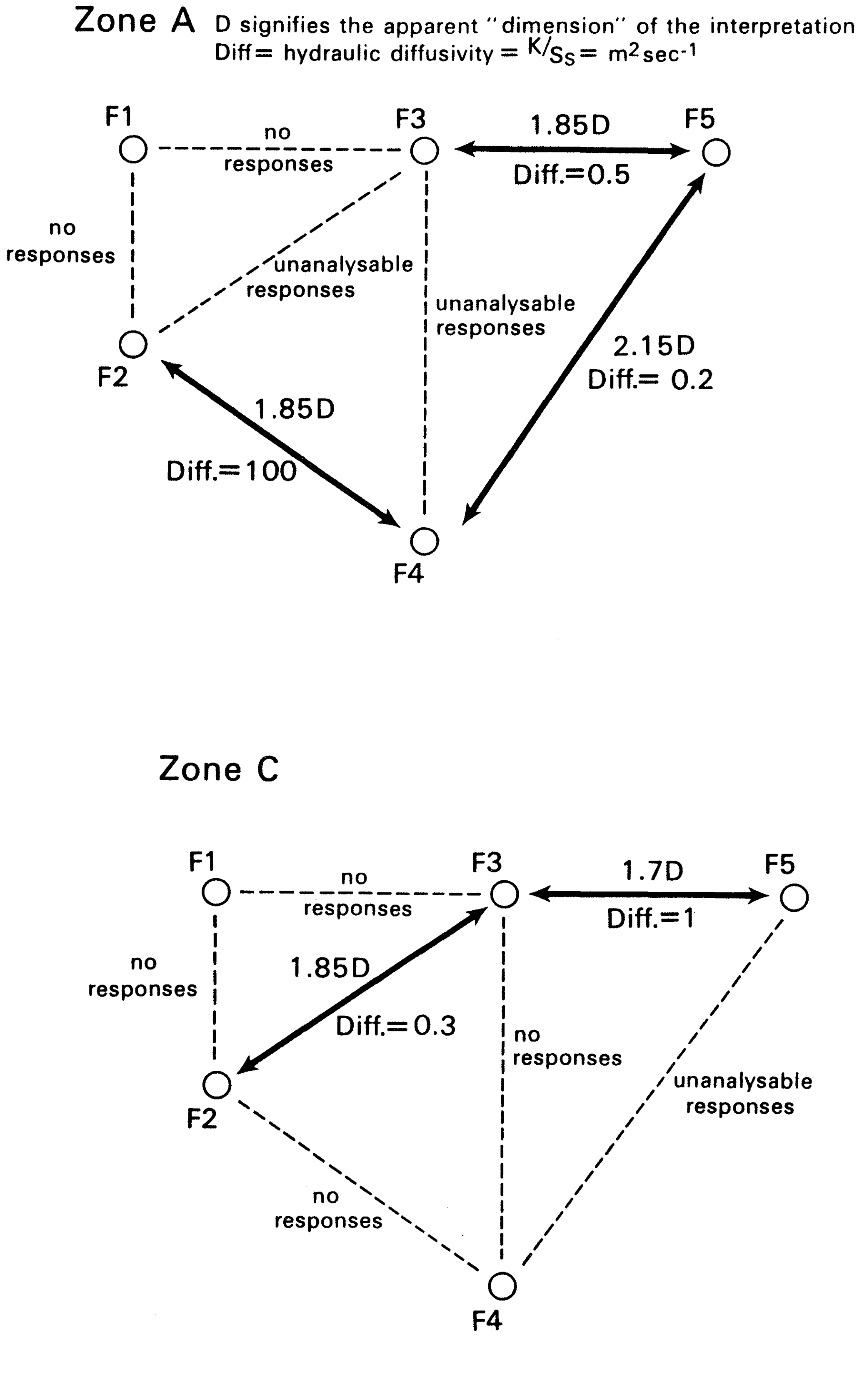


Figure 3.17 Schematic of fractional dimension results shown in relation to borehole layout:
a) Zone A b) Zone C

3.4 SINGLE BOREHOLE HEAD MEASUREMENTS

3.4.1 Introduction

In reporting the results of the hydraulic testing within the Crosshole Project , it has been the intention to divide the results into sections based on the inherent scale of the measurement. Thus although the single borehole phase of the testing is reported in Section 3.2 above, it is reported only in terms of the small-scale properties of the rocks derived from the tests. The derivation of the large-scale properties from the tests is described below. It is based on the interpretation of the natural long-term disposition of head around the mine opening. This was observed as environmental heads during the single borehole testing.

3.4.2 Basic data

The basic data was gathered during the normal single borehole testing as the value of environmental head determined in each test. The results for all the boreholes after "sifting" using the KSIFT program are shown in Figure 3.18. They are depicted as heads relative to the datum of the 360m drift level, that is the instrument drift where the equipment was located. This level is used as the base-line of each profile or, in cases where heads below this level occur, it is marked as a dashed line. It is apparent that they are generally higher in the north of the site than the south. Another general trend in the data is for regions of low head to occur towards the end of boreholes away from the instrument drift. This is caused by the presence of the old drift in this region. The presence of the instrument drift at the "left hand edge of the diagram" should depress heads in that region as water flows towards it. Its presence is just discernible in boreholes F4, F5 and F6 but not in the other boreholes. The most general appearance of the data is one of random fluctuation. This is especially evident in F1 and F2 but this may be due to the early measurement of the data and the less head-sensitive measurement technique. However it was seen in Section 3.2.3.3 that head was not an entirely random fluctuation and it seems likely that high K zones might be associated with locally anomalous heads.

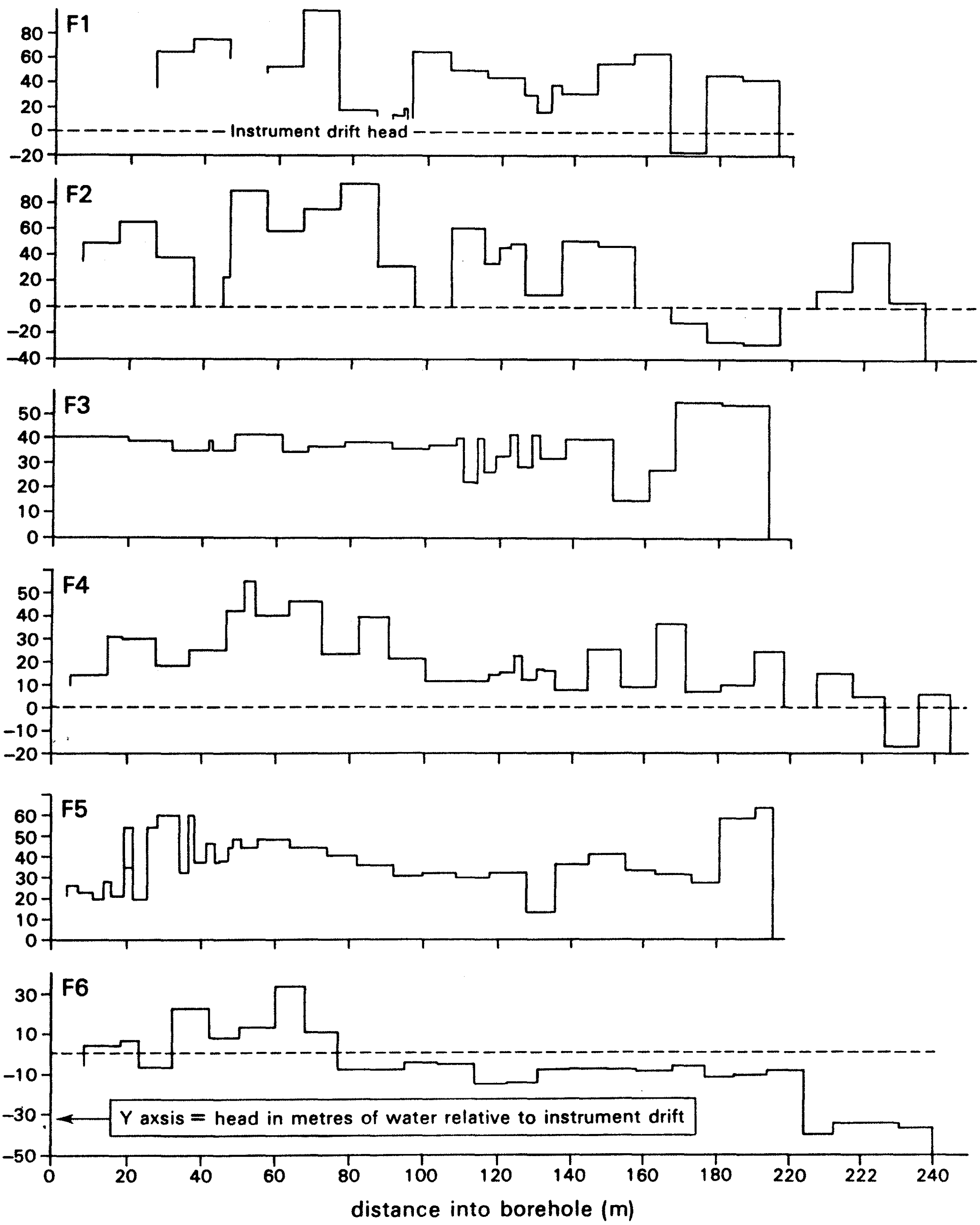


Figure 3.18 Profiles of head for the boreholes of the Crosshole Site

3.4.3 The concept of head anomalies

The problem with locally anomalous heads and their perception is that head variations are imposed upon a variable background. It is evident however that the heads are not what would be expected if the rock were a homogeneous porous medium. This is illustrated in Figure 3.19a). The essence of homogeneous rock is a smooth head distribution in response to a severe disturbance such as the "old drift" of the Crosshole Site. If the rock contains a sparse network of highly conductive features then a much more variable head distribution results (see Figure 3.19b). If the number of highly conductive features is increased then the rock's response becomes gradually again more like that of homogeneous rock (i.e. Figure 3.19a) except that the overiding large scale hydraulic conductivity of the rock would then be that of the features. In this way it is possible to visualise variable head as an indicator of heterogeneity. One particular aspect of this consideration is that a highly conductive feature does not need to actually intersect the borehole since the head associated with it will pertain over a larger region. This is particularly important in situations where channelling is suspected.

In order to evaluate the disturbance caused by a particular feature it is necessary to know what the homogeneous response would have been if the high K feature were not there. It is possible to calculate the homogeneous response which results in the minimum amount of difference between the measured heads and those predicted on a homogeneous basis. The equation used for this was the simplest available, that of Goodman and others, (1965):

$$Q_0 = \frac{2\pi K H_0}{\ln\left[\frac{2H_0}{r}\right]} \qquad [11]$$

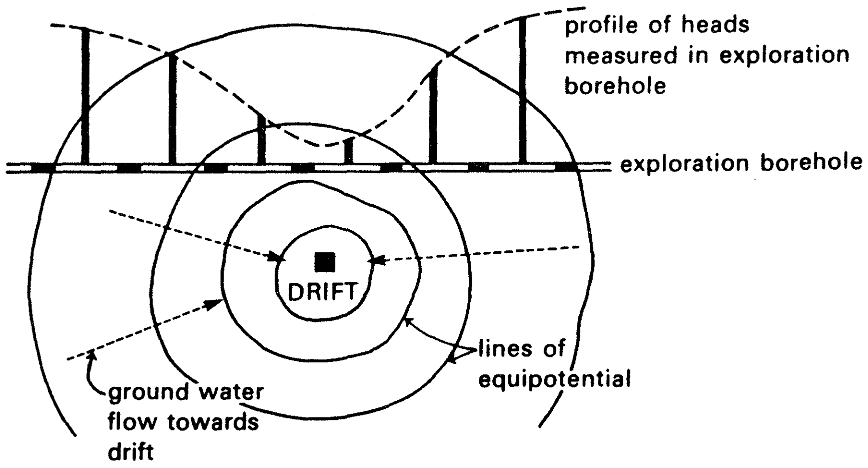
where H_0 is the height of the water table above the tunnel

r is the tunnel radius

Q_0 is the inflow rate to the tunnel per unit length

Since the equation assumes steady state, it is only valid if the water table is not drawn down by the inflow to the tunnel. This equation was applied to data assuming inflow into both the instrument drift as well as the old drift with a form of watershed some distance in-between. For the purposes of this evaluation the unit inflow rate referred to in Carlsson and others, (1983) was used. This inflow rate was undoubtedly rather large being an approximation for the whole mine

a) effectively homogeneous rock



b) heterogeneous rock (ie with highly conductive features)

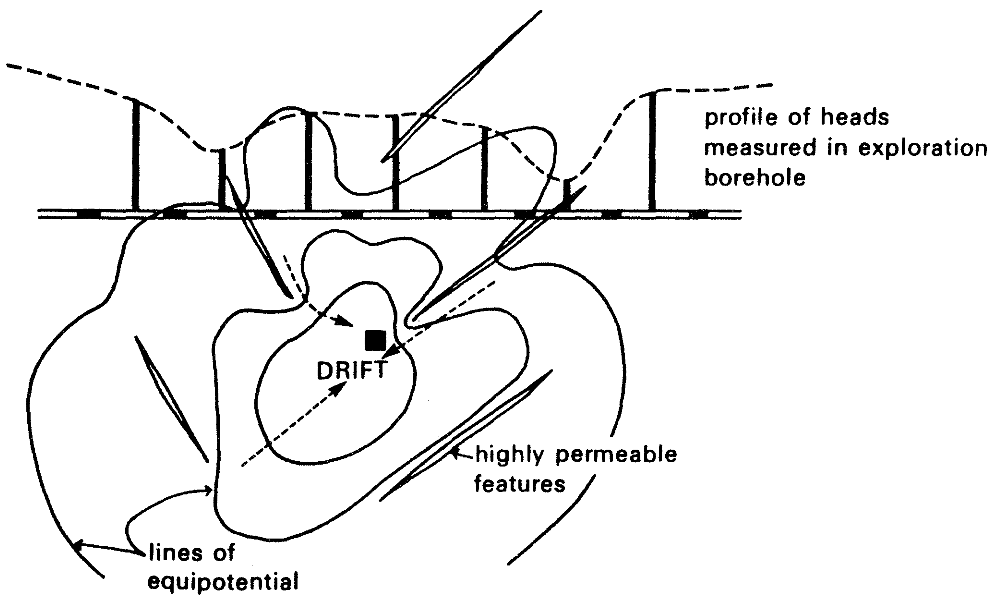


Figure 3.19 The effect of heterogeneities on the measured profiles of head: a) homogeneous rock b) heterogeneous rock

workings. A minimum was sought by calculating the total head anomaly for a series of K values starting at 1×10^{-9} m sec^{-1} and increasing in logarithmic steps of 0.05 for each borehole

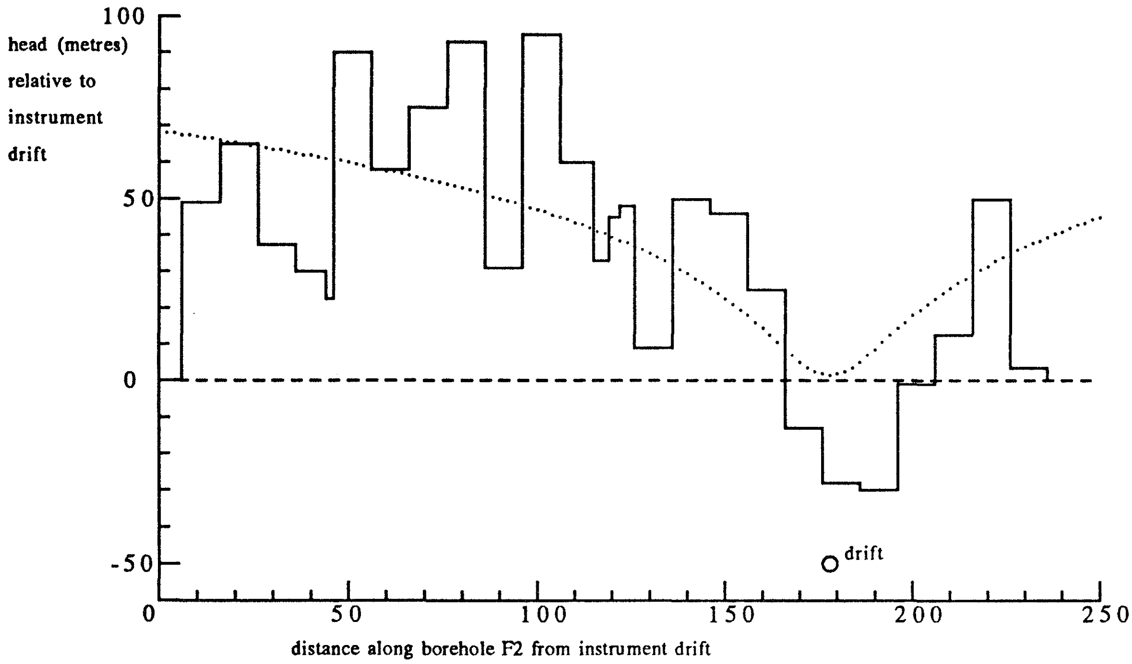
Two examples (boreholes F2 and F5) of the results of this approach are shown in Figure 3.20. It is apparent that the highly variable heads measured in F2 (likewise F1) give rise to a large number of possible anomalies. F5 is probably a little more representative of the rest of the results though the "watershed" evident in the measurements does not seem to coincide with the calculation. A closer coincidence between measured and calculated could be obtained by changing the rock so that it was anisotropic. If this were done then the anisotropy would need to be orientated so that the vertical component of hydraulic conductivity was larger than the horizontal. In the interests of simplicity and because a unique solution would be impossible this was not carried out.

An interesting facet of this approach is the value of K which was derived from the minimum head anomaly solution for each borehole. Hence:

F1 - K = 2.4 $\times 10^{-8}$ m sec^{-1}
F2 - K = 2.5 $\times 10^{-8}$ m sec^{-1}
F3 - K = 2.8 $\times 10^{-8}$ m sec^{-1}
F4 - K = 3.6 $\times 10^{-8}$ m sec^{-1}
F5 - K = 2.9 $\times 10^{-8}$ m sec^{-1}
F6 - K = 5.6 $\times 10^{-8}$ m sec^{-1}

It should be borne in mind that the value of derived K is dependent directly on the assumed inflow rate of 0.25 l/min per m of tunnel. This is undoubtedly too large: probably by one or two orders of magnitude which would bring the large scale response down to the values seen by other workers (i.e. Gale and others, 1982). It is however interesting to note the level of agreement achieved through the head data compared to the K data given in Table 3.3.

B/H F2 - minimum head anomaly results [K = 2.51E-08 m/sec]



B/H F5 - minimum head anomaly results [K = 2.88E-08 m/sec]

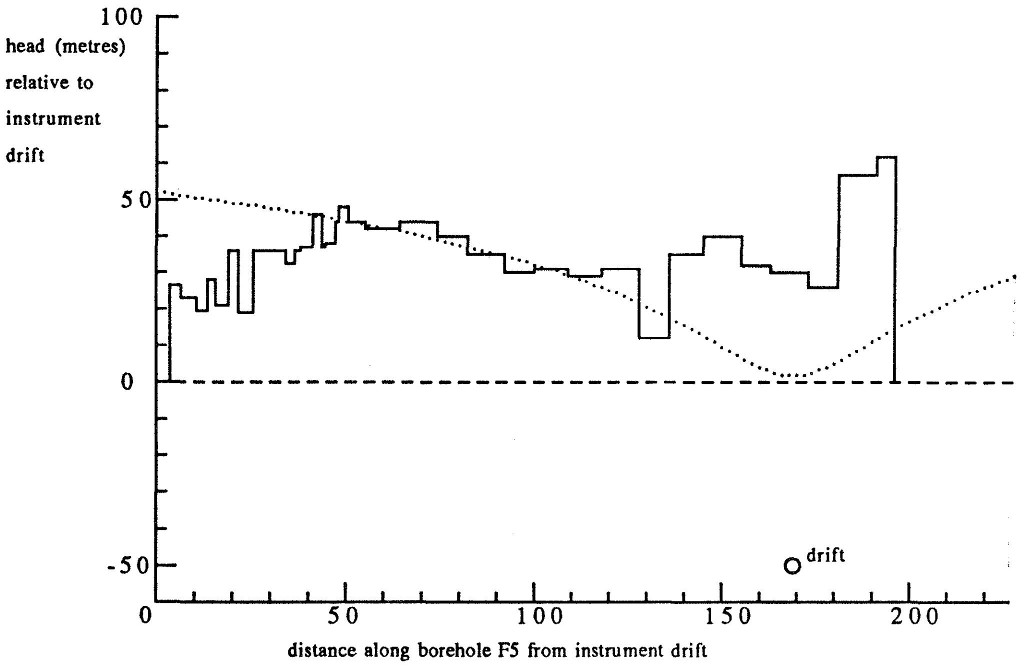


Figure 3.20 Minimum head anomaly calculations for F2 and F5

4. DISCUSSION

4.1 FRACTIONAL DIMENSIONS

The crosshole tests were best interpreted best using a flow concept involving fractional dimensions. It is assumed in Noy and others, 1987 that the smaller the dimensions of the hydraulic test under consideration in a fractured rock then the smaller the fractional dimension appropriate to analysing the test. If the results from the crosshole measurements, which have an actual scale of a few tens of metres, show dimensions less than two then it is reasonable to expect that the single borehole testing was similarly affected. This would be especially the case for tests such as pulse tests with a small radius of influence.

In an effort to gain an insight into the manner in which fractional dimensions might affect the slug and pulse test results, a fractional dimension slug test analysis has been produced (Barker and Noy , in preparation). Initial output of this model in terms of some type curves for α values (related to specific storage) in the range $1x10^{-3}$, $1x10^{-6}$ and $1x10^{-10}$ for 1-D, 2-D and 3-D are given in Figure 4.1. These show that when dimension is large then analysing the data using standard techniques (i.e. Cooper and others, 1967) will result in very small values of specific storage (S_s). The opposite result will also occur; that is that small dimension tests will yield derived values of S_s which are too large. If Figure 3.12 is re-examined then it is possible that this explains the high specific storage values.

In the work of Carlsson and Olsson, 1985a) also at the Stripa mine, it was deduced that there were a considerable number of "linear" responses in the build-up tests. These are sometimes interpreted in the oil literature as fractures along the length of the well-bore but in the Stripa mine it seems more appropriate to ascribe this behaviour to channelling.

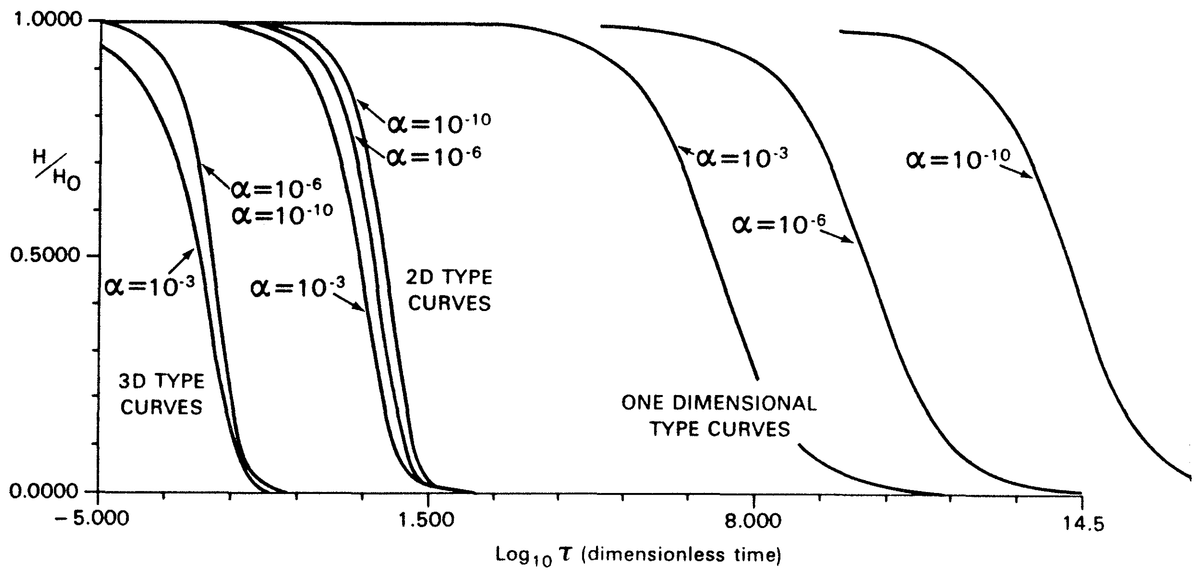


Figure 4.1 Slug test dimensional responses

4.2 THE GROUNDWATER FLOW SYSTEM AT THE CROSSHOLE SITE

The old drift on the far side of the old mine workings from the instrument drift is the major sink in the system comprising the Crosshole Site. The fracture zones intersecting this drift and penetrating the fan-array of boreholes conduct water through the Crosshole site. One zone in particular at the bottom of F6 carries a considerable amount of water and there is almost no head drop between the bottom of F6 and the elevation of the water table in the old drift. Once groundwater enters this zone at the bottom of F6 it must then rise within the zone and probably exits into the old drift somewhere very close to where Ex 144 and Ex 116 intersect (see Figure 1.2).

The other zones which seem to have an impact on the flow system are the two zones which were investigated by the sinusoidal testing, Zones A and C. Throughout most of the site these appear to be "high-head" zones indicating that the bulk of their area is in a direction away from the old drift and its low head. The bulk of the rock in the Crosshole Site takes almost no part in this pattern of large-scale flow. Similarly, the instrument drift is a minor effect.

The zones themselves are discontinuous features probably consisting of sparse networks of fractures. For instance, Zone L (the major feature at the bottom of F6) appears from the radar data to intersect the end of F4. However this highly conductive feature in F6 with undoubtedly low heads elsewhere does not have the same effect in F4 as in F6. It practically drains F6 and reduces the whole borehole level to 40 m below the instrument drift head. It seems, when considering the drainage potential of individual features, that the properties in the immediate vicinity of the feature/borehole intersection are the controlling factor. Hence the same general feature can be intersected a number of times but only when a borehole intersects a major flow channel will the feature produce signicant flow. Additionally when this occurs the borehole will cause a significant disturbance in the overall groundwater flow system.

5. CONCLUSIONS

The hydraulics programme of the Crosshole Project had roughly two aims, to "calibrate" the geophysical methods and to evaluate sinusoidal testing. The calibration of the geophysical methods is dealt with in another report (Olsson and others, 1987). In evaluating sinusoidal testing a wide range of hydrogeological issues have been raised, ranging from straightforward technolological considerations to the fundamentals of how groundwater flow is conceived.

The programme showed that it is possible to design and construct a complex set of computer-controlled equipment and operate it regularly in the mine environment. The innovative aspects of the equipment were the use of the computer for test operation and close control of all hydraulic fluctuations in the region of the source. This resulted in good quality data with a high resolution and a close adherence to the analytical assumptions underlying the test. Some individual aspects of the equipment which were novel and worked well were:

- the use of rubber cone sealing of the boreholes during testing to reduce time involved in moving
- the use of a second pump to control the "rest-of-borehole" zone
- the use of a reference pressure system
- the use of computer-protected differential pressure transducers

The single borehole testing was relatively standard in the techniques which were employed but consistent interpretation was slightly hampered by the mixture of equipment which occurred. This results more from the different emphasis and reliability associated with the different approaches than from any specific shortcomings.

The sinusoidal testing had attributes which were not expected. Firstly it proved very easy to create a sinusoidal fluctuation since it requires neither rapid changes of flow rate or head or long periods of steady conditions. The computer produced sinusoidal fluctuations which were ideal. The main unexpected aspect of sinusoidal testing is its sensitivity to the correct assumption concerning the geometry of flow during a test. The attributes which were expected were those concerning perception of the signal against a changing background. This proved easy in practice and results were easily adjusted for drift during the test. Another aspect was the return to equilibrium following a period of testing which ran according to expectation.

The analysis of the sinusoidal tests resulted in a new analysis having to be adopted. Whilst this was time consuming it was also illuminating in that other data began to be explicable in the same light. The development of the fractional dimension analysis represents a first step towards flow concepts which have a universal application. It seems possible that it represents a practical method for deriving general hydraulic properties of channelled fracture zones. These zones are the most difficult hydrogeological scale to work at because they are neither single geometrical entities nor effective equivalent porous media. This general index of response in a field test may thus provide information which can be simulated by the current range of network models.

On a practical level it appears that many tests have been misinterpreted in terms of a 2-D response where some dimension closer to 1-D would have been more appropriate. There is evidence in the tests reported here that some of the slug and pulse tests contained a response which probably resulted from flow in channels.

In general it is clear that the fractional dimension approach requires further investigation. Even at this early stage it provides fresh insights into the hydraulics of fracture zones.

Another aspect of analysis which deserves further work is the steady state approach to the measurement of the large scale heterogeneity. It contains an aspect of remote sensing which is not contained in other hydraulic testing techniques. Briefly the use of head data to pinpoint anomalous rock either intersecting the borehole or closeby provides a method for checking the zones of interest selected by geophysical methods.

The use of geophysics to pinpoint areas or zones of interest was essential to the application of the forms of crosshole testing referred to above. The tomographic images of both radar and seismics proved to be the most easily interpreted data in terms of hydraulically active zones. However since these were also the most time-consuming they were not available until later on in the programme. The single borehole radar reflection data were extremely useful in the early stages of the work but had a tendency to identify too many features.

The Crosshole Site proved ideal in its behaviour as a fractured rock. It was seen that the rock is quite regularly fractured though around 10% of the tested length yielded results indicative of unfractured rock. The assumption that the matrix rock had a K of 1×10^{-12} m sec^{-1} and a specific storage of 1×10^{-6} m^{-1} appeared to be in reasonable agreement with the results of the testing except in the vicinity of some fractures. In many instances a value for K of 1×10^{-11} m sec^{-1} may well be more appropriate.

The bulk of the rock does not take part in regional flow. Instead it is concentrated to particularly active channels contained loosely within fracture zones. These channels regularly branch and disappear and there is some evidence that when they branch their hydraulic diffusivity decreases. Of the two zones investigated by the crosshole sinusoidal method, Zone A appears to have a larger dimension than Zone C. This indicates that Zone C is a sparser network of channels than Zone A.

A major result of the Crosshole Hydraulic Programme has been the necessity to examine many hydrogeological preconceptions. This has perhaps been the most lasting of the results.

6. ACKNOWLEDGEMENTS

The authors would like to thank the staff of SGAB, particularly Olle Olsson, Mikhael Sehlstedt, Lars Falk and Eric Sandberg for all their help and assistance. Additionally our thanks go to Hans Carlsson, Bengt Stillborg and Gunnar Ramqvist of the Stripa Project who made our tasks easier. Finally we acknowledge the help of a large number of our B.G.S. colleagues, in particular Jean Alexander, David Noy and John Barker.

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