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The Fracture Zone Project – Final report

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September 1993

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ABSTRACT (ENGLISH)

This report summarizes the work and the experiences gained during the Fracture Zone Project at the Finnsjön study site. The project is probably the biggest effort, so far, to characterize a major fracture zone in crystalline bedrock. The project was running between 1984–1990 involving a large number of geological, geohydrological, geochemical, and geomechanical investigations.

The methods used for identification and characterization are reviewed and discussed in terms of applicability and possible improvements for future investigations. The discussion is exemplified with results from the investigations within the project.

Flow and transport properties of the zone determined from hydraulic tests and tracer tests are discussed. A large number of numerical modelling efforts performed within the Fracture Zone Project, the INTRAVAL Project, and the SKB 91–study are summarized and reviewed.

Finally, occurrence of similar zones and the relevance of major low angle fracture zones in connection to the siting of an underground repository is addressed.

ABSTRACT (SWEDISH)

Denna rapport sammanfattar det arbete och de erfarenheter som erhållits under Sprickzonsprojektet i Finnsjöns försöksområde. Projektet är förmodligen det största i sitt slag utfört i syfte att karakterisera en större sprickzon i kristallint berg. Projektet pågick under åren 1984–1990 och involverade ett stort antal geologiska, geohydrologiska, hydrokemiska och bergmekaniska undersökningar.

Metoder använda för identifiering och karakterisering av sprickzoner diskuteras angående tillämpbarhet och möjliga förbättringar för framtida undersökningar. Diskussionen exemplifieras med resultat från undersökningarna inom projektet.

Zonens flödes- och transportegenskaper erhållna från hydraultester och spårämnesförsök diskuteras. Ett stort antal numeriska modelleringar, utförda med varierande koncept för flöde och transport, utförda inom Sprickzonsprojektet, INTRAVAL-projektet samt SKB 91-studien, summeras och diskuteras.

Slutligen behandlas uppträdandet av liknande zoner samt relevansen av dessa i samband med platsvalet för ett underjordiskt förvar.

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SUMMARY

The groundwater flow and transport of solutes in crystalline bedrock is governed by the distribution of fractures and fracture zones in the bedrock as they constitute the main pathways for groundwater flow. The localization and characterization of potential pathways for groundwater flow and transport of solutes are essential for the safety assessment analyses of a repository for spent nuclear fuel. Another important aspect is the role of fracture zones regarding the long–term mechanical stability at the site.

Efficient methods for the detection and characterization of fracture zones are also of importance for underground construction. Passage of fractured, water yielding parts of the rock may need special precautions and arrangements. When locating underground caverns and holes for waste deposition, fracture zones with unfavorable qualities (i.e. water flow, rock movement, rock fallout, etc.) will be avoided.

The main objectives of this report are to summarize the experiences gained during the Fracture Zone Project and to highlight the achievements and lessons learned during the progress of the project. In particular, the methods used for identification and characterization of fracture zones are discussed in terms of their applicability. The role of the fracture zones regarding radionuclide transport from a repository and regarding the mechanical stability of the repository is also discussed.

The objectives of the Fracture Zone Project was:

- to study the genesis, character, age, classification, and definition of fracture zones also including literature studies and case histories,

- to determine flow and transport characteristics of fracture zones,

- to study the geochemistry of fracture zones including water chemistry, redox capacity, fracture mineralogy, and the chemical rock–water interaction,

- to study the rock mechanics of fracture zones including rock stability, deformation properties, rock stresses and their impact on flow and transport.

These objectives implied a major challenge for the investigators as no methodology for this kind of investigation was established at the start of the project.

The studied fracture zone, Zone 2 at the Finnsjön study site, was investigated over a 6 year period using a large number of methods. The genesis, character and age of the fracture zone was determined by extensive geological investigations including lineament mapping, outcrop mapping, and core mapping. In total 6 new boreholes were drilled into Zone 2 in which a comprehensive geophysical logging programme was performed. New methods like borehole radar and tubewave was shown to add substantial information to the interpretation of the geometrical framework of fractures and fracture zones. The project also demonstrated the benefits of a close collaboration between experts from different fields.

The main difficulty recognized during the project was the identification of low angle structures from ground surface geological and geophysical investigations. Also identification in boreholes may be difficult. However, new tools like the borehole radar and improvements of ground surface methods like reflection seismics have increased the possibility of locating and determining the extension of low angle fracture zones.

Flow and transport characteristics of the zone was investigated by means of a large number of single-hole hydraulic tests, interference tests, and tracer tests. Many new methods and concepts were used and found to constitute improvements that could be included in future site investigations. Piezometric measurements were, for the first time, used systematically to monitor head in sectionized boreholes. Several large scale interference tests were performed using multiple-well, multiple-section monitoring of pressure responses and also including tracers. These measurements and methods were shown to provide a large input to the geohydrological characterization of the zone.

The project also implied a systematic use of tracer tests for determination of hydraulic as well as transport parameters (i.e flow porosity, dispersivity, fracture apertures, etc). In situ measurements of groundwater flow was performed using dilution tests. These tests could confirm the low groundwater flow rates in the deeper parts of the zone as indicated by the hydrochemical investigations. Dilution tests in long borehole sections (180 m) was also performed and shown to work well.

In addition to the above mentioned tests, two large scale tracer tests were performed to determine the transport characteristics of Zone 2, the radially converging test and the dipole test. Both tests were shown to be highly applicable for characterization of fracture zones in crystalline rock. New methods and concepts for injection and sampling were developed and new tracers were tested. The results of these tests have given substantial input to the knowledge of flow and transport in fracture zones and also for the design of future tracer tests in crystalline rock.

The interference tests and tracer tests also constituted the basis for a large modelling effort. A sequence of modelling steps including predictions and subsequent calibrations, was performed within the project. Several modelling efforts were also made within the INTRAVAL Project and the SKB 91-study using a variety of modelling concepts for flow and transport. The sequence of tests and the use of predictive modelling as a design tool has served as a catalyst for the interaction between the modelers and experimentalists involved in the project. The predictive modelling with the 2–D porous medium model has also illustrated that it is possible to predict the head distribution of the system fairly well in the scale beyond 300–500 meters, while in the near–region one has to include local heterogeneities, i.e. areas with higher or lower transmissivity or anisotropy, in order to make good predictions. The transport could also be predicted fairly well. However, the local heterogeneities still need to be better accounted for.

The Fracture Zone Project has clearly demonstrated that low angle fracture zones are likely to be very important for bedrock stability, rock stress regimes and groundwater flow. Observations at Finnsjön and other sites investigated indicate that at least one low angle fracture zone is likely to be found in the upper 500–1000 m of the crystalline bedrock. However, no zone of the same magnitude as Zone 2 has been found during the Swedish site investigation programme. Thus, it is important to discuss the siting of a repository in relation to this expected fracture zone. Based on the results of this project a siting below a low angle or subhorizontal zone seem to be preferable.

1. INTRODUCTION

The main objectives of this report are to summarize the experiences gained during the Fracture Zone Project and to highlight the achievements and lessons learned during the progress of the project. In particular, the methods used for identification and characterization of fracture zones will be discussed in terms of their applicability. The role of the fracture zones regarding radionuclide transport from a repository and regarding the mechanical stability of the repository will also be discussed. Finally, the report will focus on the applicability of the results to other fracture zones and to investigations of fracture zones in general.

1.1 BACKGROUND

The groundwater flow and transport of solutes in crystalline bedrock is to a large extent governed by the distribution of fractures and fracture zones in the bedrock as they constitute the main pathways for flow . The localization and characterization of potential pathways for water flow and transport of dissolved radionuclides are essential for the safety assessment analyses of a repository for spent nuclear fuel. Another important aspect is the role of fracture zones as potential planes for future displacements.

In the earlier safety assessment studies in Sweden /KBS–3, 1983/ no credit was taken for any radionuclide retention in the fracture zones. They were considered to be pathways for transport of dissolved radionuclides with no retention, as the understanding of the flow and transport properties of fracture zones was limited. Only the relatively low conductive rock between the fracture zones and the nearest zone was considered as a geosphere barrier to radionuclide transport. It was assumed that the deposition holes had been arranged in such way that at least 100 m of acceptable rock was available with good radionuclide retention properties.

The need of an increased knowledge regarding geological, hydrogeological, and geochemical characteristics of fracture zones, and the variation of these characteristics in time and space, made it necessary to investigate a fracture zone in more detail. Of special interest for the safety of a repository, placed in the vicinity of a fracture zone, is the flow and transport of solutes in the "good" rock between the repository and the fracture zone as well as the characteristics of the fracture zone itself. It was also necessary to further develop the existing and new methods for detection and characterization of fracture zones.

In the early site selection studies for a repository of spent nuclear fuel, only a few point measurements were available from some fracture zones at each site. The data were too sparse to make a thorough 3D–characterization of a fracture zone and the surrounding rock mass. Therefore, in 1984, SKB initiated studies of fracture zones including occurrences and characteristics of fracture zones in tunnels /Palmqvist and Stanfors, 1987/, a literature review /Tirén, 1986/, and an in situ survey of a major fracture zone at the Finnsjön study site.

The Fracture Zone Project at the Finnsjön site is probably the biggest effort, so far, to characterize a major fracture zone in crystalline bedrock. The project was running between 1984–1990 involving a large number of geological, geohydrological, and geochemical investigations. Most of the performed investigations have been reported in SKB Technical Reports and Progress Reports.

There are three reports summarizing the results and discussing the conceptual model of the fracture zone determined as a result of the investigations. Ahlbom & Smellie (editors, 1989) present an overview of the Fracture Zone Project and a series of articles, later published in Journal of Hydrology (No 126, 1991), describing the geology of Zone 2 /Tirén, 1991/, the hydraulic tests and modelling of Zone 2 /Andersson et al., 1991a/, the groundwater flow conditions of Zone 2 /Gustafsson & Andersson, 1991/, the hydrochemical investigations /Smellie & Wikberg, 1991/, and finally the effects of gas–lift pumping on hydraulic borehole conditions /Andersson et al., 1991b/.

The investigations have also been used in two major modelling efforts, the international INTRAVAL Project /SKI/NEA, 1990/ and the SKB 91 study /SKB, 1992/. For the SKB 91 study, the data available from the Fracture Zone Project as well as the data from earlier site investigations at Finnsjön was compiled /Andersson et al., 1991c/. A separate report presenting the main geologic and tectonic characteristics of the Finnsjön site and its surroundings was also published /Ahlbom & Tirén, 1991/ as a basis for the SKB 91 study.

1.2 OBJECTIVES OF THE FRACTURE ZONE PROJECT

The objectives of the Fracture Zone Project was /Ahlbom et al., 1985/:

- to study the genesis, character, age, classification, and definition of fracture zones also including literature studies and case histories,
- to determine flow and transport characteristics of fracture zones,
- to study the geochemistry of fracture zones including water chemistry, redox capacity, fracture mineralogy, and the chemical rock–water interaction,

- to study the rock mechanics of fracture zones including rock stability, deformation properties, rock stresses and their impact on flow and transport.

These objectives implied a major challenge for the investigators as no methodology for this kind of investigation was established at the start of the project. Therefore, new techniques and instruments for characterization of fractures and fracture zones had to be developed in order to achieve the scientific goals of the project.

2. INTRODUCTION TO THE FRACTURE ZONE PROJECT

2.1 SITE SELECTION

The major fracture zone to be investigated in detail was selected from 35 fracture zones earlier characterized in the four previously investigated study sites Kamlunge, Gideå, Finnsjön, and Fjällveden. The selection procedure was based on 20 different criteria described in Ahlbom et al. (1985). A fracture zone at the Finnsjön study site, Zone 1 (Brändan Zone), was initially considered to be the most feasible one to study. However, at an early stage of the investigations, a previously undetected major low angle fracture zone, Zone 2, was found to have a great impact on the hydrology and geochemistry of the site and therefore, it was decided to focus the study on this zone instead.

It is interesting to note that Zone 2 had remained undetected during the earlier performed site investigations although three boreholes were penetrating the zone. However, unfavorable conditions such as long distances between the boreholes and intersections of other zones at the same locations made it difficult to interpret the structures found in the boreholes as being one continuous feature. It was not until the fourth borehole was drilled, aiming to investigate Zone 1, that Zone 2 was discovered.

The main scientific reason for the selection of Zone 2 was the hydraulically active character of Zone 2 that would permit studies of the retardation properties using tracer tests under natural groundwater flow conditions. In addition, there was a general need for development of new techniques for the detection and characterization of low angle fracture zones.

2.2 FINNSJÖN STUDY SITE

The Finnsjön study site is located in northern Uppland, central Sweden, see Figure 2–1. The site has a flat topography with differences in altitude of less than 15 m. Although outcrops are common, the area is covered to 85 % by Quaternary sediments, mainly moraine. The site was originally investigated during 1977–1982 as a part of the site investigation programme for a repository for spent nuclear fuel /Olkiewicz et al., 1979/, /Carlsson et al., 1980/, /Carlsson & Gidlund, 1983/, among others. The investigations performed within the Fracture Zone Project were mainly located in the Brändan area (Figure 2–1). A summary of all investigations performed at the Finnsjön site is presented in Ahlbom et al. (1992).

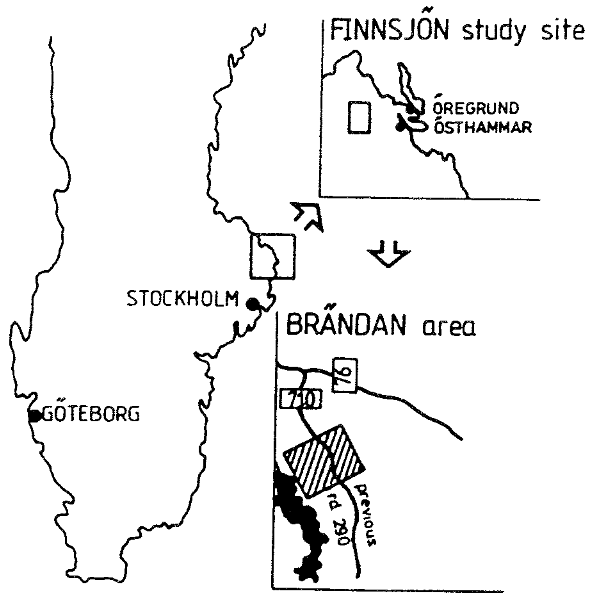


Figure 2-1. Location of the Finnsjön site.

2.3 OVERVIEW OF PERFORMED INVESTIGATIONS

2.3.1 General

The field investigation programme of the Fracture Zone Project in the Finnsjön area, performed during a 5 year period between 1984-1989, was divided into three phases. The purpose of the first phase was to establish a preliminary 3D model of the tectonic pattern and to determine the hydraulic properties of Zone 2 and the country rock. The results of the first phase was then used to evaluate the feasibility of the area for further studies. Phase 1 is described in Ahlbom et al. (1986).

Phase 2 of the Fracture Zone Project was focused on a detailed hydrogeological and geochemical characterization of Zone 2 and the surrounding rock /Ahlbom et al., 1988/. Finally, Phase 3 was concentrated on the flow and transport characteristics of Zone 2 including large scale interference tests and tracer tests /Andersson et al., 1989a/, Gustafsson & Nordqvist, 1993/, /Andersson et al., 1993/. In addition, some rock mechanical in situ measurements and laboratory tests were performed /Bjarnason & Stephansson, 1988/, /Gidlund et al, 1990/.

Besides the field investigations, which are summarized in Sections 2.3.2 - 2.3.6, a literature study was made in an early phase of the project /Tirén, 1986/. The aim was to present an overview of previously performed fracture zone studies, also aiming to define a feasible classification system for fracture zones.

2.3.2 Geological Investigations

The geology of the Finnsjön area has been extensively investigated by means of several different methods. The basic material used in the Fracture Zone Project was the investigations earlier performed for the site investigation programme in 1978–79 /Scherman, 1978/, /Almén et al., 1979/, /Jacobsson & Larsson, 1980/, /Olkiewicz & Arnefors, 1981/. These works together with ground geophysical measurements /Scherman, 1978/, /Olkiewicz et al., 1979/ constituted the basis for the planning of the investigations of the Fracture Zone Project.

The investigations performed within the Fracture Zone Project are summarized in Table 2–1 below.

Table 2–1. Summary of geological investigations performed within the Fracture Zone Project.

Investigation	**Reference**	**Report***
SURFACE INVESTIGATIONS		
Detailed lineament mapping, Brändan area	Ahlbom et al., 1986	SKB TR 86–05
Outcrop map small area of Brändan	Ahlbom et al., 1986	SKB TR 86–05
Shallow borehole profile across Brändan zone	Ahlbom et al., 1986	SKB TR 86–05
Review of fracture zones in Uppland	Ahlbom et al., 1988	SKB AR 88–09
Lineament interpretation, Uppland	Ahlbom et al., 1988	SKB AR 88–09
Geological mapping, Brändan area	Ahlbom et al., 1988	SKB AR 88–09
SUBSURFACE INVESTIGATIONS		
Drilling and core logging, KFI09 and KFI10	Ahlbom et al., 1986	SKB TR 86–05
Drilling and drilling debris characteristics, HFI01	Ahlbom et al., 1986	SKB TR 86–05
Drilling and core logging, KFI11	Ahlbom et al., 1988	SKB AR 88–09
Drilling and drilling debris characteristics, BFI01	Smellie et al., 1987	SKB AR 87–31
Drilling and drilling debris characteristics, BFI02	Ekman et al., 1989	SKB AR 89–21
Detailed core logging, KFI05 and KFI06	Ahlbom et al., 1986	SKB TR 86–05
Detailed core logging, KFI07	Ahlbom et al., 1988	SKB AR 88–09
Thin section microscopy, KFI05, KFI06 and KFI09	Ahlbom et al., 1986	SKB TR 86–05

* TR = Technical Report, AR = Progress Report (limited distribution)

2.3.3 Geophysical Investigations

The geophysical survey included both surface and subsurface measurements. Previous geophysical measurements were used and in some cases reinterpreted in more detail. The project also involved tests of some new methods, c.f. Chapter 4. The investigations performed are summarized in Table 2–2.

Table 2–2. Summary of geophysical investigations performed within the Fracture Zone Project.

Investigation	Reference	Report*
SURFACE INVESTIGATIONS		
Reinterpretation of old refraction seismics	Ahlbom et al., 1986	SKB TR 86–05
Slingram and VLF–measurements across Brändan Zone	Ahlbom et al., 1986	SKB TR 86–05
Reflection seismic parameter test	Dahl–Jensen & Palm, 1987	SKB AR 87–19
Shallow reflection seismics	Dahl–Jensen & Lindgren,1987	SKB TR 87–13
Studies of seismic activity	Holmqvist, 1987	SKB AR 87–02
SUBSURFACE INVESTIGATIONS		
Standard logging, KFI05, KFI06, KFI09, KFI10 and HFI01**	Ahlbom et al., 1986	SKB TR 86–05
Standard logging, KFI11	Ahlbom et al., 1988	SKB AR 88–09
Standard logging, BFI01	Smellie et al., 1987	SKB AR 87–31
Extended logging, BFI02***	Ekman et al., 1989	SKB AR 89–21
Reduced logging, KFI01, KFI02, KFI04, KFI07 and KFI08****	Ahlbom et al., 1986	SKB TR 86–05
Borehole radar, KFI05, KFI06, KFI09, KFI10 and HFI01	Ahlbom et al., 1986	SKB TR 86–05
Borehole radar, KFI07, KFI08 (0–200 m) and KFI11	Ahlbom et al., 1988	SKB AR 88–09
Borehole radar, BFI01	Smellie et al., 1987	SKB AR 87–31
Borehole radar, BFI02	Ekman et al., 1989	SKB AR 89–21
Tubewave measurement, BFI01	Smellie et al., 1987	SKB AR 87–31

* TR = Technical Report, AR = Progress Report (limited distribution)

** includes: borehole deviation, normal resistivity, single point resistance, borehole fluid resistivity (salinity) and temperature and natural gamma radiation.

*** : also includes caliper and sonic

**** includes: borehole deviation, normal resistivity, borehole fluid resistivity and temperature.

2.3.4 Geohydrological Investigations

The geohydrological investigations of Zone 2 and the Brändan area are the most extensive performed so far within the Swedish programme for radioactive waste disposal. Besides ordinary methods like single hole injection tests, several new methods and test designs have been applied. The investigations have also involved the performance of large scale interference tests and a number of different tracer test methods, c.f. Chapter 4. The performed investigations are summarized in Table 2–3. Most of the data is compiled in Andersson et al. (1991) and the single hole injection tests are presented in Andersson et al. (1988a). Earlier performed single hole injection tests in boreholes KFI05, KFI06, and KFI07, reported in Carlsson et al. (1980), were also used.

A large number of flow and transport modelling efforts have also been made. They are presented separately in Chapter 5.

Table 2–3. Summary of geohydraulical investigations performed within the Fracture Zone Project.

Investigation	**Reference**	**Report***
HYDRAULIC TESTS		
Single hole injection tests 5 and 20 m–sections KFI09, KFI10	Ahlbom et al., 1986	SKB TR 86–05
Single hole injection tests 2 and 10 m–sections, HFI01	Ahlbom et al., 1986	SKB TR 86–05
Single hole injection tests 20 m–sections, KFI11	Ahlbom et al., 1988	SKB AR 88–09
Single hole injection tests, method study, KFI10	Andersson et al., 1987	SKB AR 87–33
Single hole injection tests 2 m–sections in parts of KFI05, KFI06, KFI07, KFI09, KFI10, KFI11, and BFI02 (also 20 m)	Andersson et al., 1988a	SKB AR 88–08
Single hole injection tests 0.11, 2, and 20 m–sections, BFI02	Ekman et al., 1989	SKB AR 89–21
Interference test by gas–lift pumping in KFI09	Ahlbom et al., 1986	SKB TR 86–05
Interference test by air–lift pumping during drilling, BFI01	Ahlbom et al., 1988	SKB AR 88–09
Interference tests in Zone 2, pumping in BFI02	Andersson et al., 1989a	SKB TR 89–12
PIEZOMETRIC MEASUREMENTS		
Natural heads, KFI05 and KFI06	Ahlbom et al., 1986	SKB TR 86–05
Heads during drilling and pumping of HFI01	Ahlbom et al., 1986	SKB TR 86–05
Heads during air–lift pumping of BFI01	Ahlbom et al., 1988	SKB AR 88–09
Natural heads, sectionized boreholes, all except BFI02	Ahlbom et al., 1988	SKB AR 88–09
Heads during interference test in BFI02	Andersson et al., 1989a	SKB TR 89–12
TRACER TESTS		
Transport of labelled drilling fluid, KFI09–HFI01	Ahlbom et al., 1986	SKB TR 86–05
Transport of labelled drilling fluid, KFI11–HFI01	Ahlbom et al., 1988	SKB AR 88–09
Transport of labelled injection water, KFI10–HFI01	Ahlbom et al., 1988	SKB AR 88–09
Test of delay and dispersion in pumping hole BFI02	Andersson et al., 1988b	SKB AR 88–39
Test of leakage around packer during interference test, BFI02	Andersson et al., 1989a	SKB TR 89–12
Radially converging test during interference test	Andersson et al., 1989a	SKB TR 89–12
Radially converging test	Gustafsson et al., 1990	SKB AR 90–27**
Dipole test, BFI01–BFI02	Andersson et al., 1990	SKB AR 90–24**
Dilution test, BFI01, KFI06, KFI11 during pumping gradient	Andersson et al., 1990	SKB AR 90–24**
Dilution test, HFI01 and BFI01	Andersson et al., 1989a	SKB TR 89–12
Dilution test during dipole test, KFI11	Andersson et al., 1990	SKB AR 90–24**
Porosity and diffusivity of core samples, KFI06 and KFI11	Gidlund et al., 1990	SKB AR 90–34

* TR = Technical Report, AR = Progress Report (limited distribution)
** SKB TR in prep.

2.3.5 Geochemical Investigations

The geochemical investigations during the Fracture Zone Project were mainly aimed to study the geochemical character and evolution of the groundwaters in and around Zone 2. Besides the ordinary water sampling programme, also some new methods were tested, c.f. Chapter 4.4. Groundwater sampling was also performed prior to the Fracture Zone Project as a part of the site characterization. This is reported in Hultberg et al. (1981) and discussed in Allard et al. (1983). The geochemical association between the groundwaters and the fracture minerals is discussed in Tullborg & Larsson (1982). The performed investigations are presented in Table 2–4. The results are also summarized in Andersson et al. (1991) and Smellie & Wikberg (1991).

Table 2–4. Summary of geochemical investigations performed within the Fracture Zone Project.

Investigation	Reference	Report*
Surface water analysis, Brändan	Ahlbom et al., 1986	SKB TR 86–05
Drilling source water analysis, HFI01 6 levels	Ahlbom et al., 1986	SKB TR 86–05
Recovery of drilling debris and drilling fluid, KFI09, KFI10	Ahlbom et al., 1986	SKB TR 86–05
Recovery of drilling debris and drilling fluid, KFI11	Ahlbom et al., 1988	SKB AR 88–09
Recovery of drill cuttings, BFI01	Smellie et al., 1987	SKB AR 87–31
Recovery of drill cuttings, BFI02	Ekman et al., 1989	SKB AR 89–21
Groundwater analysis, KFI09 4 levels	Ahlbom et al., 1986	SKB TR 86–05
Groundwater analysis during and subsequent to air-flush rotary drilling, BFI01 5 levels	Smellie et al., 1987	SKB AR 87–31
Equilibrium modelling of the groundwaters, BFI01	Smellie & Wikberg, 1991	SKB TR 89–19
Characterization of humic substances, BFI01 1 level	Pettersson et al., 1990	SKB TR 90–29
Concentrations of Radon, Methan and Helium above Zone 1	Lindén et al., 1987	SKB AR 87–32

* TR = Technical Report, AR = Progress Report (limited distribution)

2.3.6 Rock Mechanical Investigations

The purpose of the rock mechanical study of Zone 2 was to determine the magnitude and orientation of the rock stresses versus depth and in particular variations within Zone 2. The rock mechanical conditions are summarized in Ahlbom et al. (1992) and a thorough analysis of the rock mechanical properties are given in Leijon & Ljunggren (1992). Separate from the Fracture Zone Project, the rock mass response to glaciation at Finnsjön was modelled by Rosengren & Stephansson (1990). Mechanical properties of the Finnsjön rock was earlier reported in Swan, (1977). The rock mechanical investigations are listed in Table 2–5.

Table 2–5. Summary of rock mechanical investigations performed within, and related to, the Fracture Zone Project.

Investigation	Reference	Report*
Hydraulic fracturing stress measurements, KFI06, 17 sections	Bjarnason & Stephansson, 1988	SKB AR 88–54
Deformational characteristics of Zone 2	Leijon & Ljunggren, 1992	SKB TR 92–28
Response of Zone 2 to different loadings	Leijon & Ljunggren, 1992	SKB TR 92–28
Hydromechanical conditions of Zone 2	Leijon & Ljunggren, 1992	SKB TR 92–28
Modelling of rock mass response to glaciation	Rosengren & Stephansson, 1990	SKB TR 90–40

* TR = Technical Report, AR = Progress Report (limited distribution)

3 CHARACTERISTICS OF ZONE 2

This chapter presents a brief summary of the main characteristics of Zone 2. The geological, hydraulical, and geochemical character of Zone 2 is thoroughly described in Ahlbom & Smellie (ed., 1989) and also compiled, together with all old information from Finnsjön, in Andersson et al. (1991). The geomechanical characteristics of Zone 2 are described in more detail in Leijon & Ljunggren, (1992). Transport characteristics are separately described in Chapter 5.

3.1 OCCURRENCE OF GENTLY DIPPING FRACTURE ZONES

The occurrence of gently dipping (0–30° to the horizontal) fracture zones in crystalline rock has generally been underestimated /Tirén, 1991/. The reason for this is most probably the difficulty of detecting such zones with ground geophysical methods. Also, since the site investigations involve drilling of a limited number of deep boreholes, most of the zones will only occur in one or two cored boreholes. It may therefore be difficult to determine if an altered section of the core corresponds to a fracture zone, or not, and still more difficult to correlate a possible fracture zone in one borehole with one or several possible zones in another borehole. However, in the majority of areas in Sweden where subsurface investigations for radioactive waste disposal have been performed during the last ten years (Kamlunge, Gideå, Svartboberget, Stripa, Kråkemåla, Sternö, Klipperås, and Äspö) the occurrence of horizontal to gently dipping fracture zones has been demonstrated /Carlsson et al., 1988/.

Also at the Finnsjön site there are other indications of additional gently dipping structures. Seismic reflection measurements along Zone 1 /Dahl-Jensen & Lindgren, 1987/ have recently been reprocessed and the existence of Zone 2, as well as a deeper located gently dipping zone, have been verified /Juhlin, personal. comm., 1993/. There are also indications of two other gently dipping fracture zones (Zones 9 and 11, see Figure 3–1) in the Finnsjön area /Ahlbom & Tirén, 1991/, both zones having lengths and widths similar to Zone 2 (2 km length and 50–100 m width). However, the interpretations regarding strike and dip of these two zones are uncertain due to the limited amount of data. Zone 11 may be highly transmissive, based on hydraulic tests in borehole KFI08, and thus, important for flow and transport in the area.

A study including 14 different sites in Sweden, Canada, and Finland revealed the existence of 24 gently dipping zones of a width of more than 25 m and a hydraulic contrast relative to the country rock of 100 or a width of 10 m and a contrast of 1000 /Carlsson et al., 1988/.

In the Dannemora mine, located about 15 km SW of Finnsjön, a set of parallel gently dipping zones, having a separation of about 300 m to more than 500 m, have been identified. Similar, parallel gently dipping structures, with separation of 100 to 200 m, have been found in Canada at the Underground Research Laboratory and at Hästholmen, southern Finland.

Hence, gently dipping fracture zones seem to be fairly common in crystalline rock. The introduction of new borehole investigation techniques such as borehole radar, VSP (vertical seismic profiling), and hydraulic interference tests, partly developed within the Fracture Zone Project, has increased the ability to detect gently dipping structures. Also, studies of the tectonic history of an area may indicate the probability of finding gently dipping structures.

3.2 GEOLOGY OF ZONE 2

3.2.1 Geological Evolution

Zone 2 was formed about 1700–1800 million years ago as a some hundred meters wide ductile shear zone in a country rock of grayish, medium-grained granodiorite. The ductile shear is evident in the borehole cores by the frequent occurrence of mylonites /Ahlbom et al., 1988/. This type of structure is formed during a regional tectonic event at pressures and temperatures corresponding to depths of about 5–15 km. Intrusion of red granite 1700 million years ago caused alteration of the granodiorite and reactivation of existing zones of weakness. The most pronounced effect was the hydrothermal alteration of the bedrock adjacent to water conducting shear zones and fractures, causing a distinct red coloration of e.g. Zone 2 /Tirén, 1991/.

The next period of deformation influencing Zone 2 occurred about 1000–1100 million years ago and resulted in reactivation of shear zones, block faulting, and fracturing of the host rock. Fracture infillings of prehnite are typical for this period. Fractures overprinting the prehnite-infilled fractures are rare outside the fracture zones indicating that the transport of fluid in the rock was controlled by the fracture zones. This is also supported by infillings of pinkish red laumontite restricted to Zone 2.

Then, 600 to 900 million years ago, Zone 2 was displaced by Zone 1 and transport pathways were opened in Zone 2 adjacent to Zone 1. This is indicated by a random scatter of Fe-oxyhydroxide infilled fractures in Zone 2 close to Zone 1 while away from Zone 1 these infilled fractures become more regularly distributed along distinct levels /Tirén, 1991/. This suggests that the transport of water became more restricted, occurring within distinct levels of Zone 2. During this period a major uplift and peneplanization occurred, resulting in the sub-Cambrian peneplain which roughly coincides with the ground surface of today.

The distribution of different types of infillings indicates an overall decrease in temperature with time and that few new fractures appeared. Younger fractures seam to be restricted to minor sections within and immediately above Zone 2. However, the growth of low temperature minerals on older, high temperature minerals, indicates that reactivation of existing fractures occurred several times throughout the later stages of the geological evolution of Zone 2.

Possible late tectonic movements were briefly studied by Ahlbom & Tirén (1991). They concluded that there have been no or only small movements along Zone 2 after the ductile deformation ceased. The conclusion was based on observations of a dike on both sides of the zone and of borehole radar reflectors interpreted to continue without displacement across the zone.

3.2.2 Geometry and Fracture Model of Zone 2

Zone 2 is defined in nine boreholes located within an area of about 1500 x 500 m in the northern part of the Finnsjön Rock Block, see Figure 3-1. In the eastern part the upper boundary of Zone 2 is almost planar, oriented in N28W/16W, and located between 100 to 240 m below the ground surface, see Figure 3-2. The location of the lower boundary is less distinct. The average width of the zone is about 100 m. In the western part Zone 2 occurs in borehole KFI07 at a depth of 295 m which is shallower than expected from the dip in the eastern part. Hence, Zone 2 cannot form a continuous planar surface within the whole Brändan area.

The lateral extension of Zone 2 can be certainly defined only in the southeast part of the area where it is bounded by Zone 1. The extension of Zone 2 towards the northeast and southwest is more speculative as there are no boreholes in these parts of the area. Fracture zones 4 and 12 in Figure 3-1 may possibly be boundaries for Zone 2, as indicated in Ahlbom & Tirén (1991), but Zone 2 may also outcrop close to the intersection of Zone 1 and Zone 3 as indicated in Ahlbom et al. (1988).

Although Zone 2 is expressed as a 100 m wide, more or less altered zone, the fracture frequency is generally low, except for two to five sections in each borehole. These sections are narrow, 2-5 m wide (in some cases up to 30 m) and are mainly located at the upper and lower boundaries of the zone. In Figure 3-3 a tentative, early stage, fracture model of Zone 2 is presented. The zone is a planar shear zone from which minor, moderately inclined zones (splays) project upwards into the overlying rock block. Tension fractures are formed at the root zone of the splays and the splays are offset by vertical shears parallel to the direction of the displacement /Tirén, 1991/.

The late fracture characteristics of Zone 2 resemble a compound fault /Martel, 1990/, where some of the early fractures have been reactivated in a late tectonic phase to develop a compound fault structure. Characteristic for such a structure is a stepwise lateral extension of the zone which may explain why the zone cannot be followed as a planar surface between the eastern and western parts /Ahlbom & Tirén, 1991/.

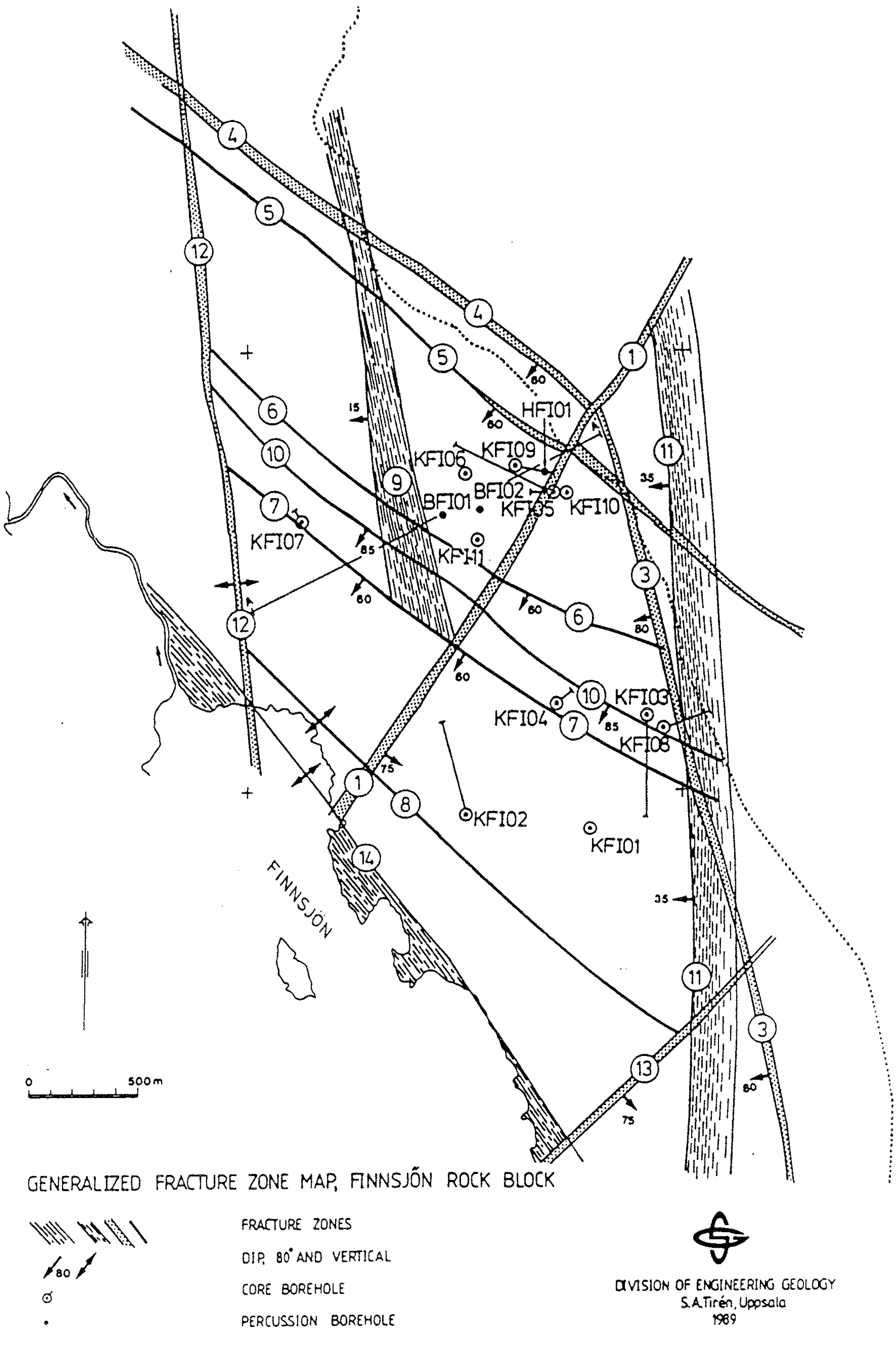


Figure 3–1. Generalized map of fracture zones and boreholes at the Finnsjön Rock Block /Ahlbom & Tirén, 1991/.

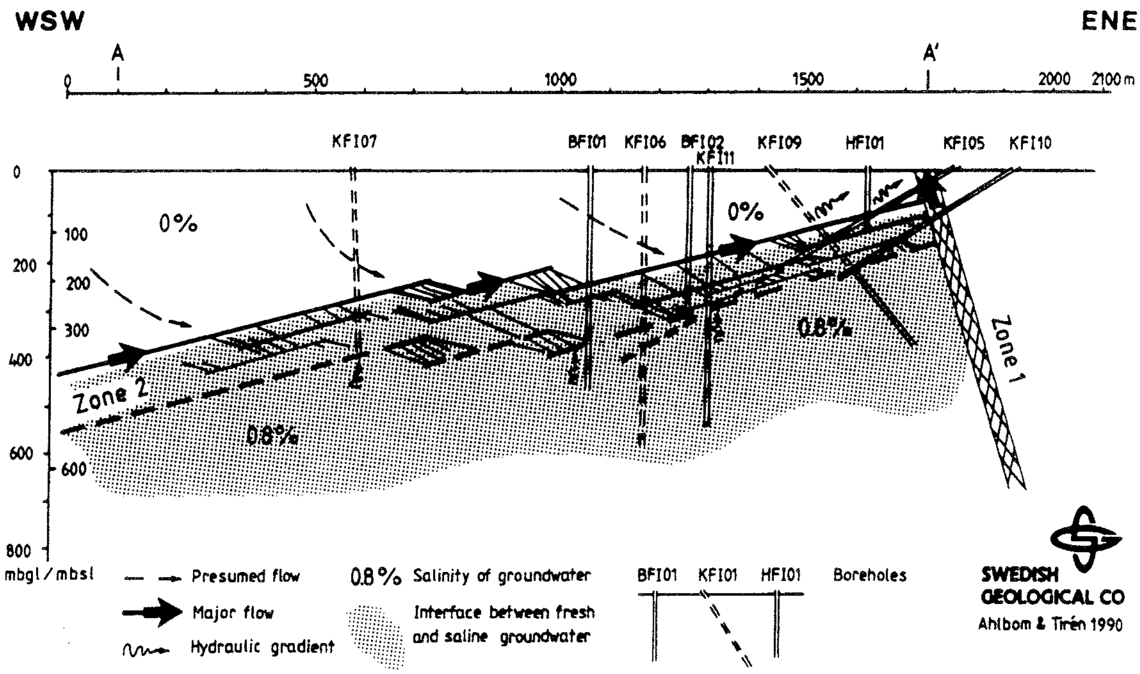


Figure 3–2. Schematic cross-section showing late fracture characteristics of Zone 2. Location of the profile is shown in Figure 3–1.

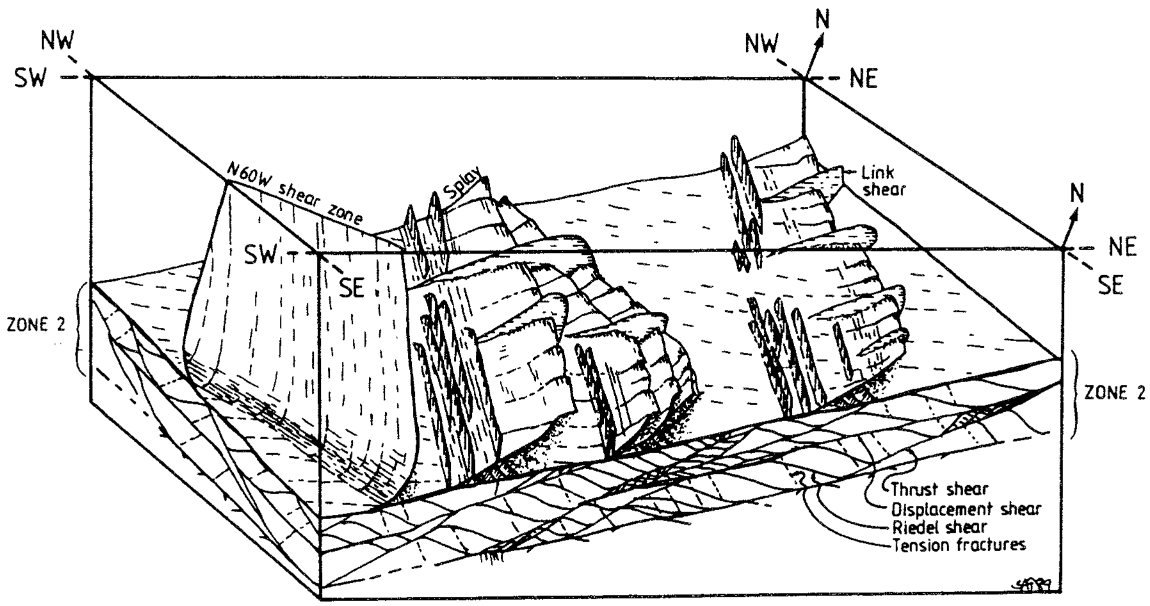


Figure 3–3. Tentative fracture model of Zone 2 at an early stage as it was formed in a thrust regime with maximum compression to the NE /Tirén, 1991/.

3.2.3 Geomechanical Character

Rock stress measurements performed with the hydraulic fracturing technique /Bjarnason & Stephansson, 1988/ show that rock stresses are as expected in Swedish bedrock both in terms of magnitudes and directions. The measurements reveal thrust fault conditions from surface down to approximately 500 m, below which strike-slip fault conditions are indicated. There appears to be no evidence of major stress disturbances associated with Zone 2 although a slight stress discontinuity is indicated, see Figure 3-4.

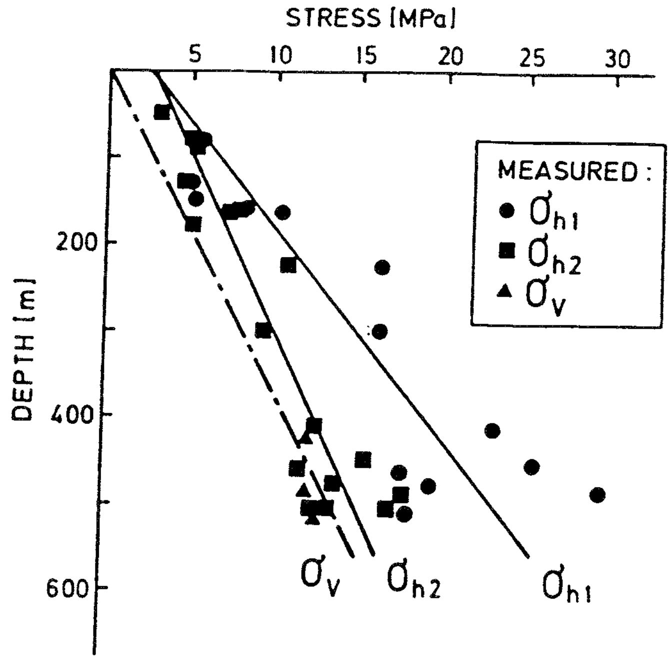


Figure 3-4. Measured stress magnitudes versus depth, borehole KFI06. After Bjarnason and Stephansson (1988).

Leijon & Ljunggren (1992) determined the deformational characteristics of Zone 2 by estimates of the modulus of deformation in three different ways, see Figure 3-5. The results were found to be consistent with the regional stress pattern of large scale field data according to the Fennoscandian Rock Stress Data Base /Stephansson et al., 1987/.

From a rock mechanical point of view, Zone 2 may not be considered as a distinct feature but rather as a part of the continuous rock mass. The features of major concern are the narrow highly transmissive parts of the zone, especially at and close to the upper bound of Zone 2 /Leijon & Ljunggren, 1992/. These narrow discontinuities can transfer normal compressive forces, resulting in only local disturbances in the vertical stress field. However, stress changes induced by glaciation and deglaciation may cause reactivation and shear displacements.

The conclusion that Zone 2 does not create any major stress anomaly is not valid for fracture zones in general. It is well known that large-scale fracture zones may alter stress conditions significantly, e.g. the major fault zone at Forsmark which showed a major stress discontinuity /Bjarnason & Stephansson, 1988/.

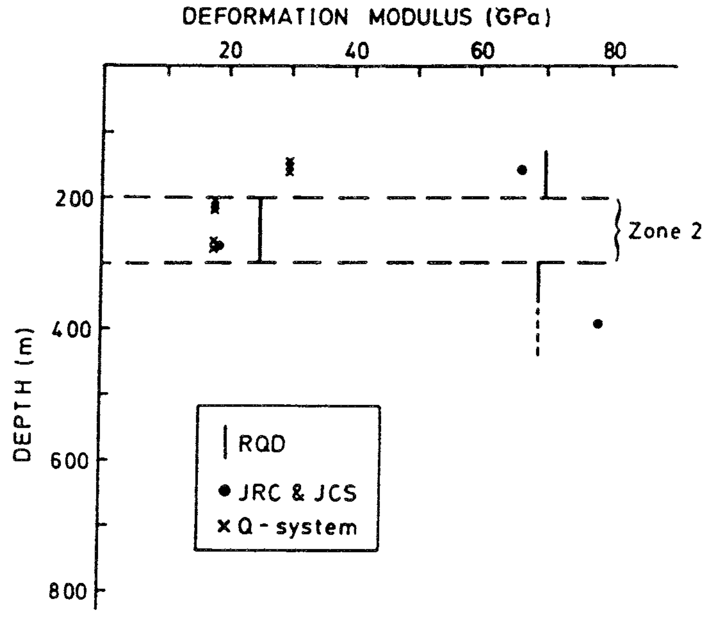


Figure 3-5. Calculated rock mass modulus at Finnsjön study site as a function of depth. Summary of results obtained with three different methods applied /Leijon & Ljunggren, 1992/.

3.3 HYDRAULIC CHARACTER

3.3.1 Hydraulic Conditions

The hydraulic character of Zone 2 has been extensively investigated by means of a large number of hydraulic tests and tracer tests performed within nine boreholes penetrating the zone. The zone typically consists of two to five narrow, highly transmissive ($T=1-4 \cdot 10^{-4}$ m^2/s), sections as illustrated in Figure 3-6 by the results from the single hole injection tests for borehole BFI01. Above the zone, a general decrease of transmissivity towards depth is observed. This decrease is interrupted by the upper bound of the zone, where transmissivity increases by one to four orders of magnitude. Thus, the hydraulic contrast between the upper part of the zone and the overlying rock is very high. Detailed hydraulic testing indicates that the highly transmissive sections have a width of only about 0.5 m, c.f Chapter 4. Interference tests and tracer tests have shown that the upper highly transmissive "subzone" is hydraulically interconnected between the boreholes over a distance of several hundred meters.

At lower levels in Zone 2 there are several narrow parts with high transmissivity separated by bedrock with low transmissivity. These "subzones" cannot be geometrically correlated as planar structures between the boreholes. However, there are indications, from the large scale interference tests performed as well as from the radially converging tracer test, that these structures are well interconnected, at least over distances of 150 m. This is also in agreement with the fracture model (Figure 3-3). The interference tests also indicate that Zone 2 responds as a porous medium in the far field (>400 m) while the near region is influenced by local heterogeneities /Andersson et al., 1989a/.

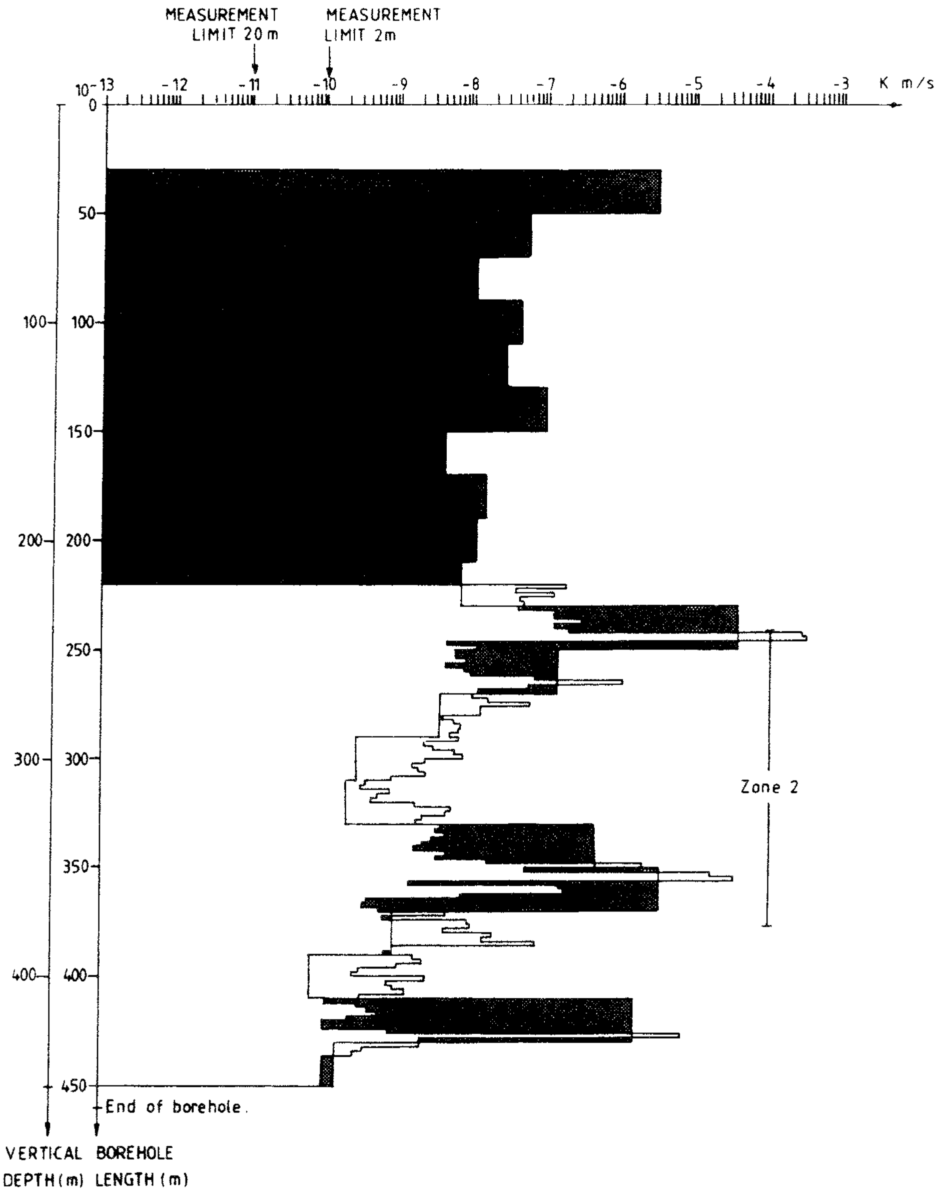


Figure 3-6. Hydraulic conductivity versus depth in 2 m- and 20 m-sections in borehole BFI01 /Andersson et al., 1988a/.

A certain anisotropy of the hydraulic properties along the zone was also observed during the interference tests and the tracer tests /Andersson et al., 1991/. The interference tests also indicated that Zone 2 is delimited by hydraulic boundaries.

3.3.2 Head and Flow Conditions

Registration of groundwater heads /Gustafsson & Andersson, 1991/ shows that in the western deeper part of Zone 2, groundwater from the upper bedrock recharges into the upper part of the zone while in the eastern, more shallow parts, water is discharged to Zone 1. Head measurements performed in a few points in the upper part of Zone 2 indicate a main flow direction towards ENE with a gradient of about 0.2–0.3% (Figure 3–7) /Gustafsson & Andersson, 1991/. It should be noted that there are considerable uncertainties in the interpretation of the piezometric measurements due to the varying salinities along the boreholes and the registration methods adopted, c.f. Chapter 4.3.1. However, independent information from a tracer test performed during drilling of borehole KFI11 /Gustafsson & Andersson, 1991/, where tracer was found to be transported a distance of 440 m to borehole HFI01 under mainly undisturbed flow conditions, confirms the piezometric measurements.

Both piezometric measurements and pressure differences, registered during the hydraulic single–hole tests, indicate that only small pressure gradients exist within Zone 2, both laterally and vertically /Andersson et al., 1991/.

Based on natural flow rates determined with the point dilution method and estimates of possible infiltration rates from the upper bedrock, it can be concluded that regional groundwater flow to a large extent contributes to the groundwater flow in Zone 2 /Gustafsson and Andersson, 1989/.

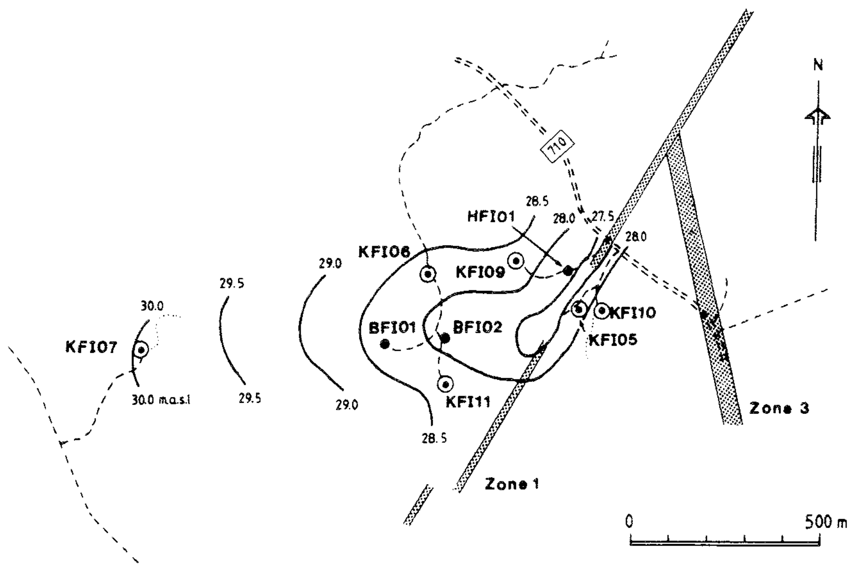


Figure 3–7. Estimated distribution of hydraulic head in the upper part of Zone 2 based on piezometric measurements /Ahlbom et al., 1988/.

3.4 HYDROCHEMICAL CHARACTER

3.4.1 Chemical and Isotopic Character of the Groundwaters

The groundwater chemistry of Zone 2 and the surrounding bedrock is characterized by the sharp distinction between the non-saline (calcium-bicarbonate type) and saline waters via a transition zone of mixing (i.e. Zone 2). This is illustrated in Figure 3-8 by the increasing electrical conductivity values downwards through the zone in borehole KFI09. The pH, in contrast, shows a decrease with depth from just above Zone 2, which is contrary to that normally indicated by Swedish groundwaters at increasing depth /Smellie & Wikberg, 1991/.

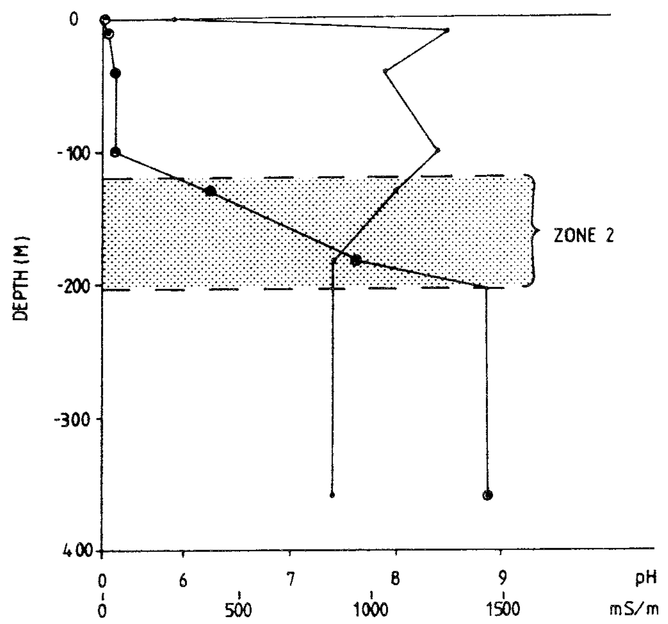


Figure 3-8. Variation of pH and electrical conductivity with depth in borehole KFI09 /Ahlbom et al., 1986/.

The stable isotope data shows very little variation with depth and can be considered to be meteoric in origin. Radioisotope data clearly indicate the extent of a young, near-surface derived component characterized by high amounts of modern-derived carbon and significant tritium contents. With increasing depth and salinity the groundwater rapidly exhibits a reduction in modern-derived carbon with a minimum at the lower horizons of Zone 2. At these depths no significant tritium has been detected /Smellie & Wikberg, 1991/.

The redox conditions, defined by the Eh and the contents of ferrous iron, uranium, and dissolved oxygen, are reducing within Zone 2. Sampling in borehole BFI01 showed highly oxidizing conditions, but this was attributed to perturbations during drilling (air–flush percussion drilling) when air at high pressure was forced into the zone.

Based on the hydrochemical data available, the upper part of Zone 2 seems to act as a "sump" whereupon saline water from below the zone is mixed with non–saline water from above the zone. Interestingly, the mixed water has a similarly high carbonate content as the non–saline water. This implies the water has been subject to carbon dioxide diffusion after mixing with the saline water. Below Zone 2 the water has a constant composition with increasing depth which indicates that there is very little, if any, flow. This is also supported by the moderate to high uranium activity ratios recorded from borehole KFI09 /Smellie and Wikberg, 1989/.

The fact that Zone 2 acts as a barrier between the different types of groundwaters is not a unique occurrence, similar conditions have been found elsewhere, e.g. in Finland. However, the Fracture Zone Project constituted the first detailed investigation of the phenomenon.

3.4.2 Evolution and Origin of the Finnsjön Groundwaters

The origin of the saline groundwaters in the Finnsjön area is debatable. Several different theories are discussed in Smellie & Wikberg (1991). It is evident that the origin of these waters is complex. Based on comparisons with similar saline groundwaters in Finland, Canada, and at Forsmark close to the Finnsjön area, Smellie & Wikberg (1989) conclude that the Finnsjön groundwaters are coastal marine in origin but later also modified by water/rock interactions and possibly also other salt water sources. Apparent radiocarbon ages range between 9 000–15 000 years, which is somewhat younger than expected based on comparison with the Forsmark groundwaters (23 000 years old). This is believed to be due to carbon–14 dilution.

The stages of evolution of the Finnsjön groundwaters can be summarized as follows /Smellie & Wikberg, 1991/:

- During the melting phase of the Weichselian ice sheet (20 000 years ago) infiltration of fresh meltwater occurred. These waters locally mixed with existing groundwaters which may have been influenced over long periods of geological time from the accumulation of residual igneous/metamorphic fluids, limited rock/fluid interactions, and salt water sources of unknown origin.

- During the marine transgressions of the Yoldia sea (8 500–9 500 years ago) and the later Litorina sea (2 500–7 500 years ago) the area became saturated with marine saline waters, sometimes almost totally displacing the "fresh" water. The deeper these waters penetrated, or the longer the residence times, the greater the likelihood that rock/water interactions would have modified the chemistry of the groundwaters.

- This mixing/dilution of rain/glacial melt water with marine-derived saline waters has also resulted in continuous change of the groundwater isotopic signatures.

- Following isostatic uplift and exposure of the landmass, the near-surface marine water was gradually replaced by fresh water. The depth and extent of this process has been largely dependent on the regional and local hydrology. In this respect the presence of major structural weakness zones, like Zone 2, will act as hydraulic barriers resulting in entrapment of salt water at higher levels than otherwise could be expected.

3.5 CONCEPTUAL MODEL OF FLOW DISTRIBUTION IN ZONE 2

Based on the investigations and interpretations of the geological, geomechanical, geohydrological, and hydrochemical character of Zone 2, a conceptual model was presented in Ahlbom & Tirén (1991). The model (Figure 3-9) shows the main structural and hydraulic characteristics of Zone 2. The groundwater flow is assumed to take place above and in the upper, most transmissive part of the zone. Below the zone there may be some circulation of saline water directed towards the zone, but the flow rate is probably very low compared to the flow in the upper part of the zone.

The top of Zone 2 is highly permeable and constitutes a boundary between non-saline above and saline groundwaters below.

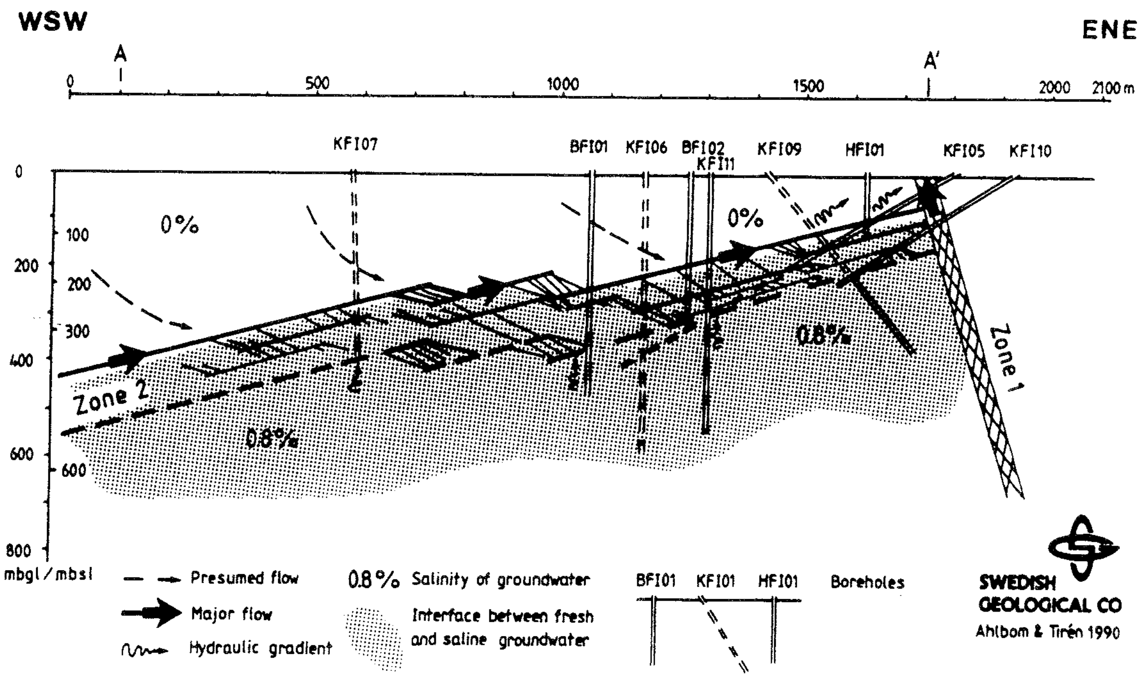


Figure 3-9. Tentative model of groundwater flow at Zone 2.

4 METHODS USED AND THEIR APPLICABILITY FOR IDENTIFICATION AND CHARACTERIZATION OF FRACTURE ZONES

The characterization of the Brändan area and Zone 2 has involved a large number of different methods. The methods, the aim of using the methods, and the applicability of the methods for site characterization is briefly described below. Examples of results are also given.

4.1 GEOLOGICAL CHARACTERIZATION

4.1.1 Methods used for Identification of Fracture Zones

4.1.1.1 General

The geological methods used for identification of fracture zones can be divided into surface and subsurface methods. At Finnsjön, the following methods were used;

Surface methods:

- lineament interpretation from air–photos, ordinary topographical maps and detailed contoured maps,
- outcrop mapping,
- field control of lineament interpretations.

Subsurface methods

- drilling and borehole core logging.

4.1.1.2 Lineament Interpretation

The first method applied in the Fracture Zone Project was to make a lineament interpretation of the Finnsjön site, about 2x3 km large, based on 1:10 000 air–photos /Ahlbom et al., 1986/. Later, in the detailed characterization phase, lineament studies covering the entire Uppland (scale 1:2 000 000), northeastern Uppland (scale 1:250 000), and Finnsjön – Södra Åsjön area (scale 1:50 000) were performed /Ahlbom et al., 1988; Ahlbom & Tirén, 1991/. Finally, a detailed interpretation based on air–photos (scale 1:30 000) was made to complement the lineament interpretation from the topographical maps /Ahlbom & Tirén, 1991/, see Figure 4–1.

One problem with the lineament interpretation is that different scales pronounces different sizes of fracture zones. A scale of 1:10 000 suppresses large features like the Brändan Zone but enhances minor fracture zones. Hence, it is important that lineament interpretations are made in different scales.

An attempt to identify the lineaments interpreted within the Brändan area, in situ, was also made. However, this was found to be difficult due to the small relief of the area. Ahlbom et al. (1988) also conclude that lineaments with a northerly trend are poorly identified in the field and could be an expression of the inland ice erosion.

4.1.1.3 Outcrop Mapping

In addition to the lineament interpretations, a detailed **map of outcrops** was made for the central part of the Brändan area in order to locate possible fracture zones in combination with the ground geophysical measurements.

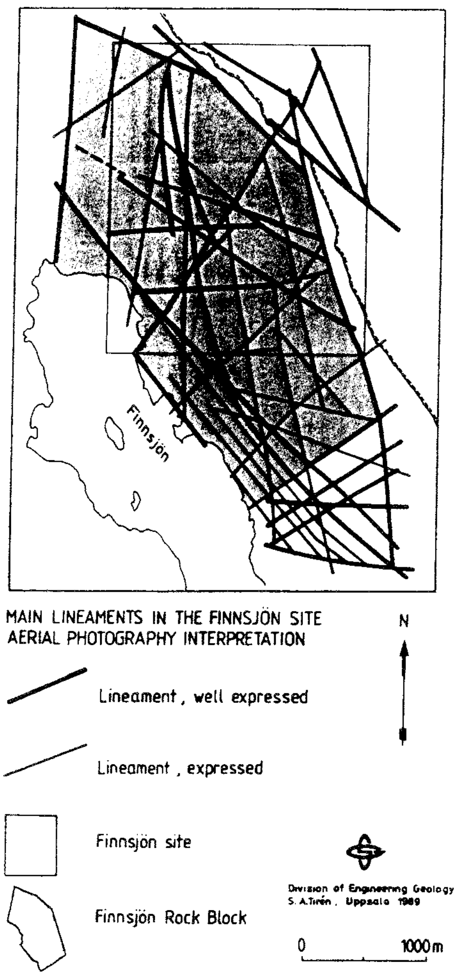


Figure 4–1. Aerial–photo interpretation of lineaments at the Finnsjön site /Ahlbom and Tirén, 1991/.

4.1.1.4 Core Drilling and Core Mapping

Based on the ground surface investigations a drilling programme was started. The first drilling phase involved two cored boreholes KFI09, KFI10, and a drilling water supply well, HFI01 (percussion drilled). These boreholes were originally directed towards the characterization of Zone 1 but as the drilling proceeded it became clear that a subhorizontal structure had been discovered. Borehole KFI10 confirmed the dip and location of Zone 1 and that Zone 2 existed. Again, this development of the project illustrates the uncertainties involved in identifying and determining the extension of fracture zones.

The geological identification of Zone 2 is based on core logging of boreholes KFI09 and KFI10, and a remapping of parts of the previously drilled boreholes KFI05 and KFI06 /Ahlbom et al., 1986/. To obtain a more certain characterization of Zone 2, borehole KFI11 was drilled and mapped, and a section of borehole KFI07 was remapped /Ahlbom et al., 1988/.

The core mapping clearly identified Zones 1 and 2 as sections of increased fracture frequency and red coloring, c.f. Chapter 3. The core mapping performed within the project put special emphasis on defining specific characteristics for identifying Zones 1 and 2, like specific fracture minerals (further discussed in Chapter 4.1.2). By doing this, it was possible to separate the respective zones in the cores.

4.1.1.5 Percussion Drilling

In percussion boreholes, where no cores can be collected, the drilling procedure itself can be used to identify fracture zones. During drilling of percussion borehole HFI01, the penetration rate of the drilling tool and water yield was monitored. Drill cuttings were collected at every third meter. The same method was later applied during drilling of the two deeper percussion boreholes, BFI01 and BFI02. Here, the drilling procedure also included measurements of the electrical conductivity of the borehole fluid, which served as a good indicator of Zone 2.

Percussion borehole BFI01 was specially designed to be drilled in steps with subsequent groundwater sampling, c.f. Chapter 4.4. Therefore, only data from the drilling was used for identification of hydraulic structures/fracture zones. Drilling penetration rate, drill cuttings, and borehole water yield all showed good agreement with the subsequent geophysical measurements and hydraulic tests, indicating presence of fracture zones /Smellie et al., 1987/.

Some disadvantages with the above described methods of a technical character occurred. The drilling penetration rate may decrease below a highly conductive zone due to inflow of water with high pressure. Also, an increase in water yield can be difficult to detect after passing through a highly transmissive zone.

4.1.2 Methods used for Characterization of Fracture Zones

4.1.2.1 General

Fracture zones imply breakages of the rock along planar domains. A fracture zone consists of more or less interconnected fractures. The intensity of the fracturing, type of fracture infillings and the degree and extent of alteration are dependent on the geologic environment during formation and later geologic history. Geological mapping and fracture surveys at the ground surface and of drill cores, together with chemical and mineralogical analyses of samples, provide information of the geological character and history of the fracture zones. This information is needed to interpret hydraulic tests and to assess transport properties of the zones.

The geological characterization of the Brändan area and Zone 2 involved the following main studies /Ahlbom et al., 1988/, /Tirén, 1991/:

- fracture mapping of outcrops
- fracture mapping of cores
- chemical and mineralogical analyses of cores
- studies of drill cuts from percussion drilling

4.1.2.2 Fracture Mapping of Outcrops

The fracture survey in the Brändan area was performed along profiles spaced 200 m apart and as a survey along a 90 m long trench of exposed rock. During the survey, the following parameters were recorded; rock types, rock alterations (especially discoloration), foliations, folds, fractures (sets and estimated spacing), fractures defining the outcrop, and character of lineaments. The 90 m long and 5 m wide trench, along which the cover of soil was removed, was mapped in detail to define the relation between fractures and morphology of the bedrock surface, and to get a statistical characterization of the fracture population.

The results of the fracture mapping showed that mapping of outcrops only gives limited information about fracture zones as they are not generally located within natural exposures of the bedrock. However, mapping of fractures forming the morphology of outcrops was found to be successful in defining the configuration of more extensive fractures (vertical as well as flat lying). The method also appeared to be a fast method to establish the configuration of fracture zones within the bedrock and is recommended as a complement to cell mapping and other time consuming techniques used for collecting fracture data for statistical analysis.

Exposing of the rock surface in areas where lineaments are interpreted to occur can be a valuable tool for verification and characterization of fracture zones.

4.1.2.3 Fracture Mapping of Cores

The geological character of Zone 2 and the country rock was determined by core logging of the six cored boreholes in the Brändan area. The parameters determined were: rock type, rock alteration (including colour), and fractures (fracture–core intersection angle and coating). Both coated and sealed fractures were mapped. No fractures in drillcores from the Finnsjön study site are oriented.

The fracture survey performed on rock outcrops formed the basis for a semi–quantitative analysis of the fracture population (three sets of fractures) in three vertical boreholes penetrating Zone 2. Fracture frequencies were calculated based on three sets of fractures identified from the surface mapping. An attempt was also made to correlate fracture characteristics with hydraulic conductivity.

Figure 4–2 illustrates a composite core log across Zone 2 in borehole KFI11. The figure shows some of the main characteristics of Zone 2, namely the red coloration at the most altered parts, the Fe^{3+}–precipitates, and the increased frequency of sealed and natural fractures. This illustrates the importance of a deeper analysis of core data. In the earlier Swedish site characterization programme, only a few attempts have been made to correlate a number of different geologic and hydraulic characteristics to a specific zone.

One of the main difficulties with the core mapping is to quantify the crushed parts of the core which, in general, are the most interesting from a hydraulic point of view. It may be very difficult and/or time consuming to determine the actual fracture frequency due to strong fragmentation of the rock. These parts of the core are also often characterized by core losses. Thus, it is important to recover as much of the core as possible in the crushed parts during drilling.

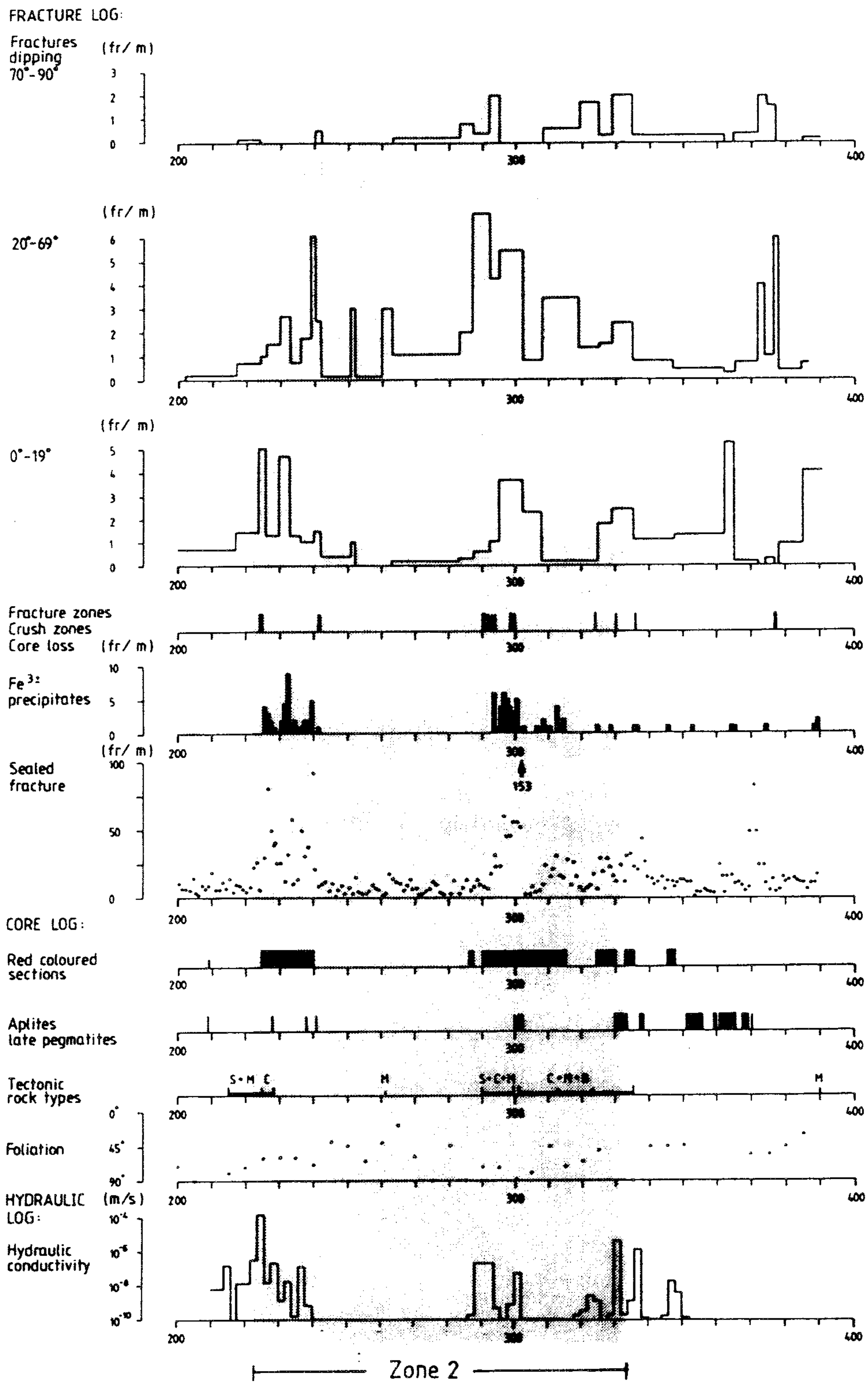


Figure 4–2. Composite geologic log and hydraulic conductivity across Zone 2; borehole KFI11, section 200–390 m. (S=ductile shear, M=mylonite, C=cataclasite, B=breccia, Arrows=slickenside striation. Foliation: 0°=horizontal and 90°=vertical).

4.1.2.4 Analyses of Drill Cores

In order to study the weathering and alteration in the granodiorite, samples for thin section microscopy were collected from three boreholes (KFI05, KFI06, KFI09) /Ahlbom et al., 1986/. By studying fracture infillings it is possible to determine if and when fractures have been reactivated in the past. This knowledge is important as earlier reactivated fractures are the most probable structures to be reactivated also in the future. Analyses of fracture minerals proved to be valuable also for identification of Zone 2 as the mineral assemblages were specific for Zone 2 and could be identified in all three boreholes.

4.1.2.5 Drill-cuttings from Percussion Drilling

Drill-cuttings were collected during drilling of all three percussion holes penetrating Zone 2 (HFI01, BFI01, BFI02). As the altered sections at Finnsjön in most cases are characterized by a change from grey to red colour, this was a good indicator of fracture zones. The characterization of drill-cuttings from the first drilled of the three percussion holes, HFI01, only involved colour and size while the later drilled boreholes, BFI01 and BFI02, involved a more detailed analysis. Samples were collected at every fifth meter and a lithological description was made.

The sampling and characterization of drill-cuttings proved to be a good method of identifying fracture zones at Finnsjön. However, there are also some difficulties associated with the analysis, as both grain sizes and sorting grade are partly functions of depth. The drill-cuttings tend to get more fine grained and well sorted towards depth as the drilling penetration rate decreases. This makes interpretations and comparisons of fracture zones more difficult and it is important to be aware of this fact when interpreting and comparing fracture zones.

Sampling at every fifth meter can be too sparse for a good characterization, bearing in mind that the most permeable sections of Zone 2 only are about 0.1-0.5 m wide. Thus, sampling at every meter is recommended.

During the drilling of BFI01 and BFI02, special efforts were made to collect all drill-cuttings in order to estimate the portion of drill-cuttings forced out into the fractures. The drill-cuttings were collected in a system of open containers which later were weighed /Smellie et al., 1987/, /Ekman et al., 1989/. The recovery of drill-cuttings was found to be relatively high for the uppermost 200 m, 80 and 97% for BFI01 and BFI02 respectively. However, after penetrating Zone 2, a substantial loss of drill-cuttings into the fractures was found and recovery rates was lowered to 41 and 71%, respectively. Hence, large amounts of drill cuttings, 1.3 and 8.4 tons respectively, is forced into the fracture system during percussion drilling.

Similar estimates of recovery of drill-cuttings from drilling of cored boreholes was also made /Ahlbom et al., 1986/. Most of the drill-cuttings below the intersection of a major fracture zone was found to be forced out into the fractures. However, the total amounts were much smaller (0.5 tons in KFI09) due to the much smaller production of drill-cuttings during core drilling.

4.2 GEOPHYSICAL CHARACTERIZATION

4.2.1 Surface Methods

4.2.1.1 General

The ground geophysical measurements performed within the Fracture Zone Project involved the following investigations:

- studies of old geophysical maps (slingram, resistivity, IP, magnetometer surveys)
- reinterpretation of old refraction seismics measurements
- slingram measurements, 10 profiles
- VLF-measurements, 10 profiles
- shallow reflection seismics
- studies of seismic activity

Ground geophysical profiles and maps were studied with the objective of defining the location and, if possible, the dip of fracture zones within the Brändan area. Most of these investigations were made in an early phase when the main effort was concentrated on the Brändan zone. However, attempts were also made to define fracture zones in the vicinity of Zone 1.

All measurements confirmed the presence of Zone 1 and also indicated some minor zones in the area. A slingram survey parallel to Zone 1 indicated minor fracture zones perpendicular to Zone 1 which corresponded very well with the geological surface mapping. In Figure 4-3 the 10 slingram profiles measured across Zone 1 is shown. The zone is clearly indicated as an anomaly but the dip direction of the zone is difficult to estimate. The figure also shows a shift in the location of Zone 1 in the two lower profiles which is consistent with the VLF profiles /Ahlbom et al., 1986/.

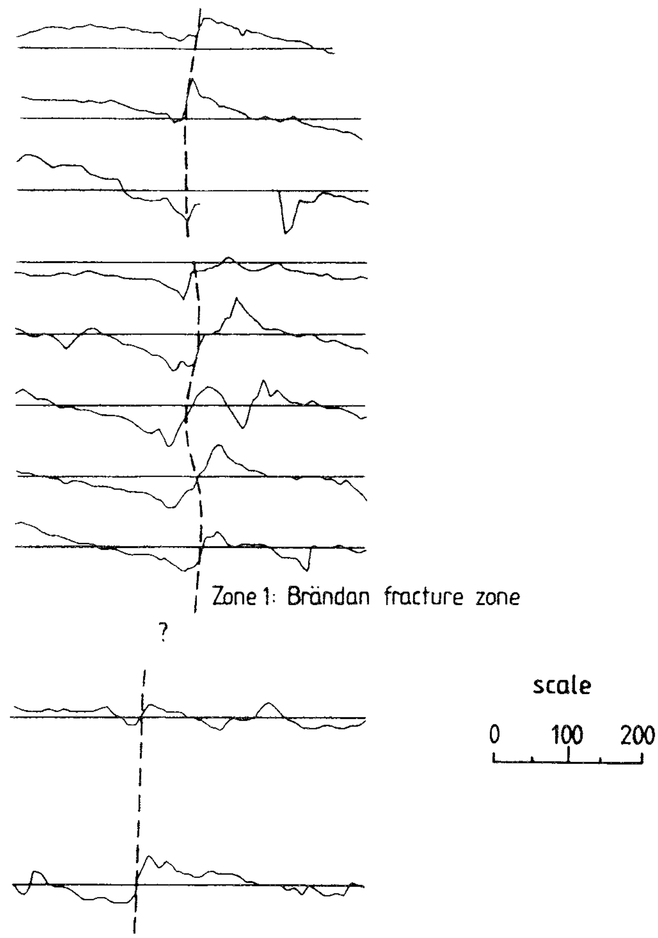


Figure 4-3. Slingram measurements in profiles across Zone 1 /Ahlbom et al., 1986/.

4.2.1.2 Reflection Seismics

The identification of low angle structures from ground geophysical measurements is very difficult for most methods. The ground geophysical method which seems to have the greatest potential to detect such structures is the reflection seismics. Therefore, a special effort was made to study the feasibility of this method. A parameter test was performed to optimize the possibility of identifying Zone 2 /Dahl-Jensen & Palm, 1987/. However, in spite of careful parameter selection (charge size, depth of charge, spacing, geophone frequency, etc) and a variety of filtering methods, the zone was not possible to detect although its presence was known /Dahl-Jensen & Lindgren, 1987/. Recently, the data have been reprocessed, including static corrections and modern filtering techniques. Preliminary results show that Zone 2 is clearly identified together with several deeper located low angle zones (C. Juhlin, pers. comm., Uppsala Jan 1993).

4.2.1.3 Seismic Activity

A special study was made to investigate the seismic activity and the relation to the larger fracture zones at the Finnsjön site /Holmqvist, 1987/. The seismic activity was monitored using five mobile seismograph stations. The investigation showed that the seismic activity at Finnsjön is low at present. Totally 10 small earthquakes could be localized of which four occurred close to major fracture zones (Zones 2 and 3). However, the accuracy was not sufficiently good to definitely relate the earthquakes to displacements along the zones.

4.2.2 Geophysical Borehole Methods

4.2.2.1 General

The geophysical borehole investigations are used both for identification and characterization of fracture zones. Anomalies indicate either the presence of a fracture or a fracture zone or changes in the rock mass properties, e.g. a change in lithology. Besides the older methods used in the earlier site characterization programme, some new methods were tested namely the borehole radar and the tubewave method. The geophysical borehole methods used within the Fracture Zone Project were:

- borehole deviation
- natural gamma
- single point resistance
- normal resistivity
- borehole fluid resistivity (salinity)
- temperature
- temperature gradient
- caliper (only percussion boreholes)
- sonic
- borehole radar
- tubewave

4.2.2.2 Borehole Deviation

The borehole deviation log is important as it determines the true location of the borehole and hence the location of structures intersected by the borehole. The borehole deviation logs for all boreholes in the Brändan area, except borehole BFI02, are presented in Ahlbom et al. (1988), while borehole BFI02 is given in Ekman et al. (1989). The logs show that the two percussion drilled boreholes, BFI01 and BFI02, deviate up to about 40 meters from the planned location at depth. Borehole deviation is important to consider in the evaluation of cross-hole test and in the geometrical interpretation of the extension and dip of fracture zones. Hence, the value of borehole deviation measurements is clearly demonstrated. Another conclusion that can be drawn from the deviation measurements is that the booster drilling technique using a high air pressure may cause large deviations of the borehole direction. All other boreholes in the Brändan area show only minor deviations.

4.2.2.3 Caliper

The caliper log determines the diameter of a borehole. Caliper logging is important both for the instrumentation of a borehole and for determination of borehole volumes in connection with point dilution measurements, in particular for percussion boreholes, c.f. Chapter 4.3. Within this project caliper logging was made only in borehole BFI02, see Figure 4-4. The log shows two narrow peaks with increased diameter corresponding to the upper and lower highly conductive part of Zone 2. Note also the good correlation with anomalies in the other geophysical logs.

4.2.2.4 Natural Gamma

The natural gamma log reveals the variations of natural gamma radiation depending on the contents of U, Th, and K in the rock. Variation in the gamma level usually corresponds to mineralogical or lithological changes in the bedrock. The method may also indicate inflow of radon charged water, but for Zone 2 these indications were weak. Instead, correlation with dikes of pegmatite and breccias were considerably better /Ekman et al., 1989/. An example of this is shown in the natural gamma log for borehole BFI02 (Figure 4-4) where large anomalies occur at 170-180 m and 186-195 m corresponding to the location of dikes, while the upper highly conductive part of Zone 2 at 204 m displays a small anomaly. In borehole KFI11 an increase in the natural gamma radiation coincides with a general increase in the fracture frequency which indicates that groundwater flow may have occurred over the entire width (about 20 m) of the fractured section, resulting in the formation of radioactive fracture minerals. It was also found that the now highly water conducting fractures in Zone 2 did not show any increased radiation, indicating that these conductive fractures are either recently formed or (more probably) that old fractures at the upper part of Zone 2 have "recently" been reopened /Ahlbom et al., 1988/.

4.2.2.5 Single Point Resistance and Resistivity

The single point resistance and the resistivity logs both indicate the presence of fracture zones and conducting minerals. The resistivity logs have greater depth penetration but less resolution compared to the single point resistance log. Both methods were used in all boreholes in the Brändan area and show almost identical patterns /Ahlbom et al., 1986/, /Smellie et al., 1987/, /Ahlbom et al., 1988/, /Ekman et al., 1989/. These methods proved to be very useful for the identification and characterization of Zone 2 and Zone 11. Especially the width of the two zones could be clearly identified as a section of significantly decreased resistivity, see Figure 4-4. In fact, the resistivity anomalies were found to be the best method to define the upper and lower

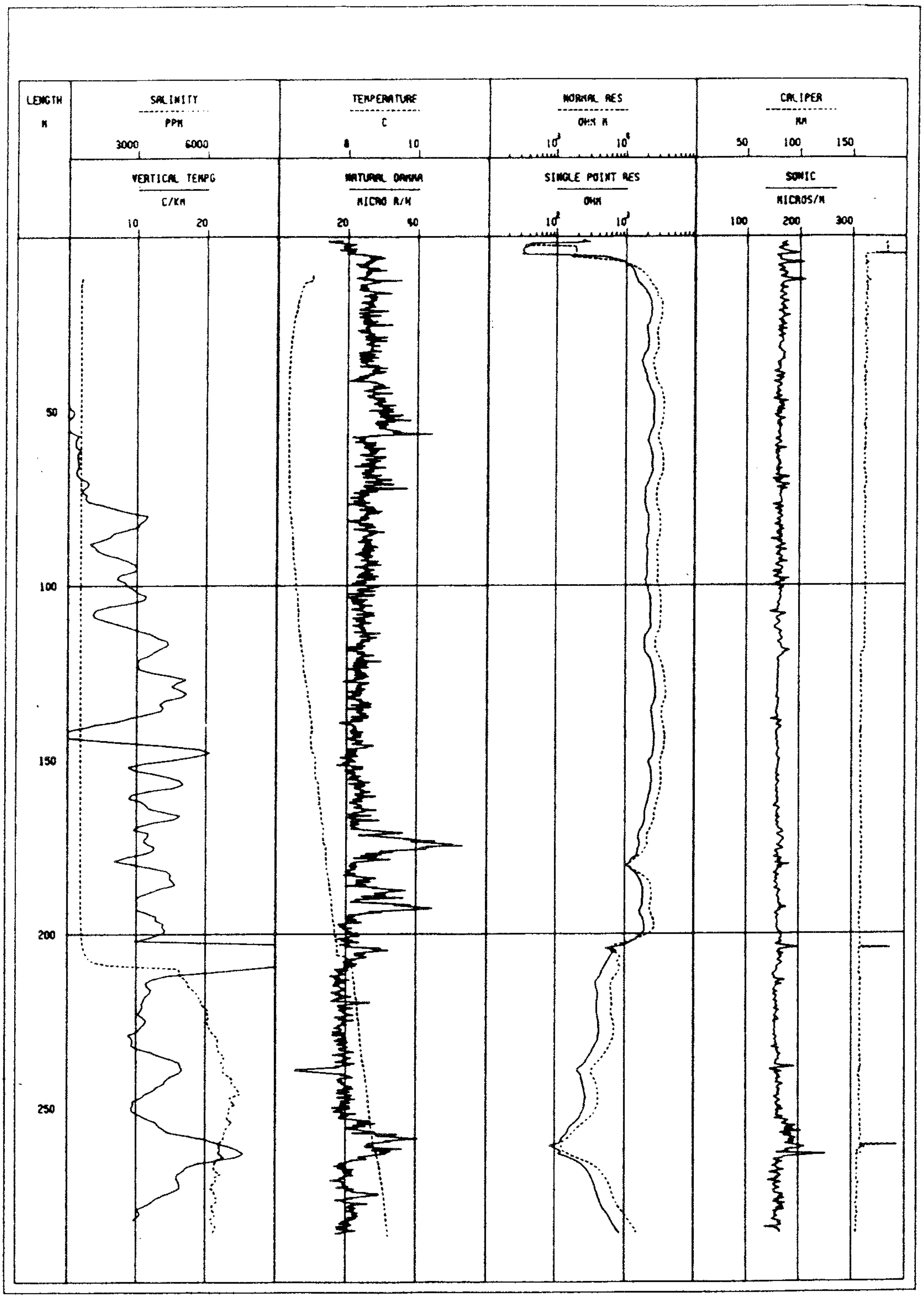


Figure 4–4. Composite geophysical log of borehole BFI02. Zone 2 is located between 204 and 280 m depth. /Ekman et al., 1989/

boundary of Zone 2 /Ahlbom et al., 1988/. Distinct anomalies also correlate very well with water conducting parts of Zone 2 for all boreholes.

4.2.2.6 Borehole Fluid Resistivity (Salinity) and Temperature

The borehole fluid resistivity (salinity) and the temperature are two parameters that may indicate inflow of water with different temperature and/or salinity. Due to the presence of saline water in Zone 2 and the sharp contrast with the fresh water above the zone this method was specially useful for determination of the upper boundary of Zone 2. The temperature also showed a instant increase of about 0.7°C at the upper surface of Zone 2 (see Figure 4–4) indicating inflow of warmer water /Ahlbom et al., 1988/. In some of the boreholes, like KFI11, BFI01, and BFI02, the salinity increase occurs somewhat below the upper highly conductive part of Zone 2. This is interpreted as an area where fresh water is infiltrating Zone 2 at the upper surface, i.e. a recharge area, while the opposite situation with saline water above the upper surface of Zone 2 occurs in the shallow parts of Zone 2 (boreholes KFI05, KFI09, KFI10, and HFI01), i.e. a discharge area (see also Figure 3–9).

4.2.2.7 Sonic Velocity

The sonic velocity log measures the time for a sound pulse to travel between two receivers. Borehole BFI02 is the only borehole where this method was used /Ekman et al., 1989/. The method displays anomalies in the water conducting parts of Zone 2 but also large variations in the upper 100 m, see Figure 4–4.

4.2.2.8 Borehole Radar and Tubewave

Two new methods, previously not used in the site characterization programme, was applied in the Fracture Zone Project, namely the borehole radar and the tubewave method. Both methods have the advantage of being able to locate water conducting zones without contaminating the borehole. This is especially important in boreholes where sampling for water chemistry is to be made, like in borehole BFI01.

The purpose of using the borehole radar was to study the extension of fracture zones and to obtain the orientation of zones relative to the borehole axis. All boreholes in the Brändan area, also the old ones, were measured. The results confirmed the existence and orientation of Zone 2 in an early stage of the investigations /Ahlbom et al., 1986/. The zone coincides in general with a decrease in velocity of the direct wave and a penetration loss of the radar waves caused by high porosity of the bedrock and the saline water in connection to the zone. An example of this is given in Figure 4–5 for borehole KFI11 where Zone 2 intersects between 225–338 m. Here, the three highly water conducting substructures of Zone 2 are clearly visible as bands of increased penetration loss, the first around 225–235 m, the second at 290–310 m, and the third at 330–350 m.

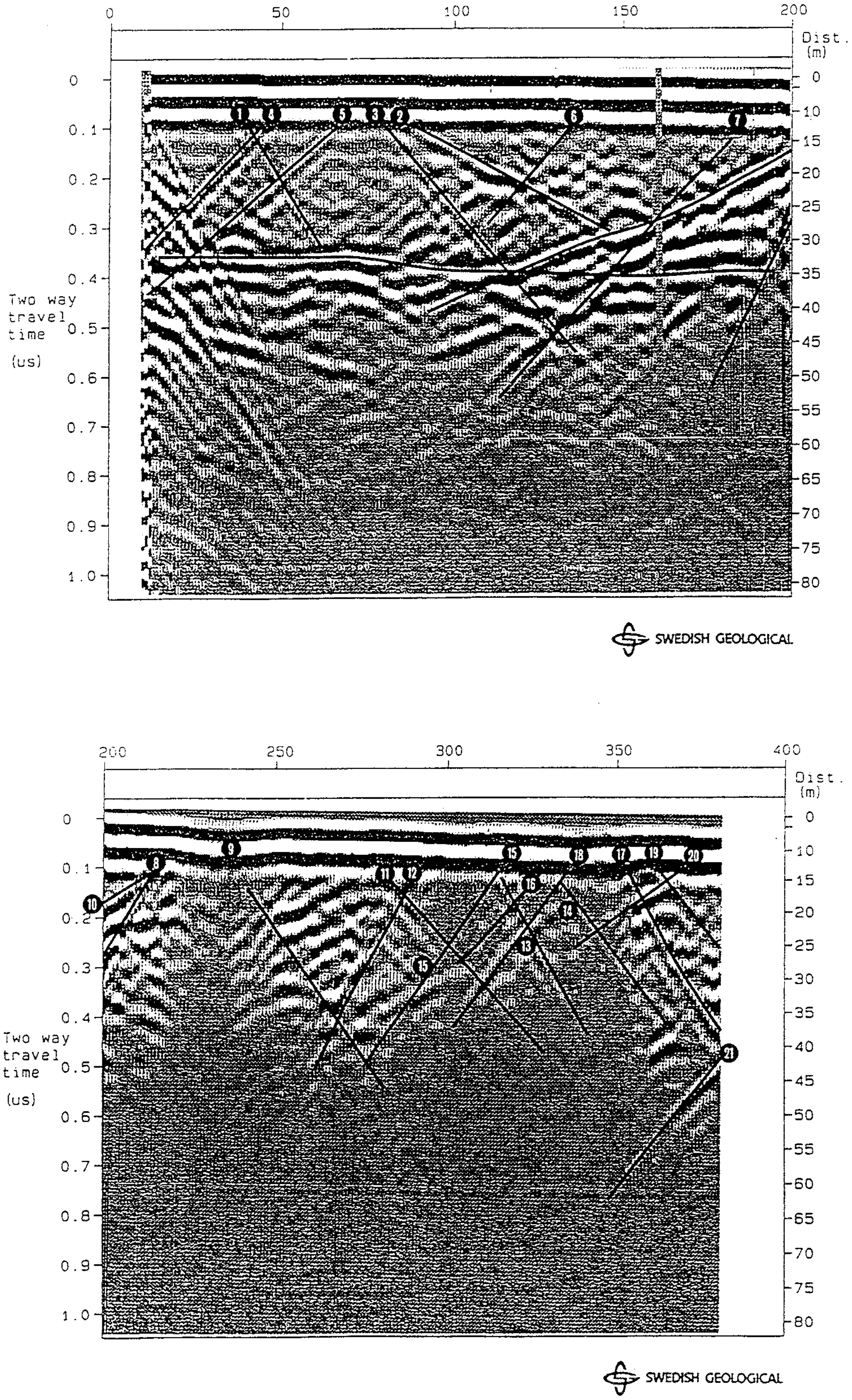


Figure 4–5. Radar attenuation maps for borehole KFI11. The numbers refer to interpreted radar reflectors /Ahlbom et al., 1988/

The borehole radar was found to be a very valuable tool for identifying structures and the determination of the orientation of zones makes the method very important for correlation of zones between boreholes. Another good feature of the borehole radar is its ability to "see" structures outside the borehole, e.g the structure below borehole KFI11 (Figure 4-5, structure no. 21) calculated to intersect the borehole axis at 422 m depth, i.e. 32 m below the bottom of KFI11, and the structure running parallel to the borehole from the surface down to 218 m depth (Figure 4-5, structure no. 8). However, it should be noted that the borehole radar also indicates many non-water conducting structures, e.g. basic dikes, and that the interpretation has to be integrated with other sources of information such as core logging and hydraulic tests. The development of a directional antenna within the Stripa Project further improves the suitability of the method. If such a possibility had been available during the Fracture Zone Project a better understanding of the geometry and its relation to the connectivity of fracture zones would have been possible.

The tubewave method was also tested in one borehole, BFI01, during the project. The method should give the position of a tubewave generator, corresponding to a water conducting fracture/fracture zone. The measurement may also give a rough estimate of the transmissivity of the fracture generating the tubewave determined from the relative tubewave amplitude. The results, presented in Stenberg (1986), shows a very good correlation with the later performed hydraulic injection tests in 2 and 20 m sections. A total of 13 tubewaves were generated and they are located exactly where high hydraulic conductivities were measured. The transmissivity estimates from the tubewave amplitudes were also relatively good, within one order of magnitude from the transmissivities determined by single hole hydraulic tests. Hence, the tubewave method appears to be a suitable method for location of water conducting structures.

Smellie et al. (1987) conclude that the two methods have a great strength, especially when they complement each other. Tubewave measurements reveal the existence and location of water conducting structures, whereupon radar measurements add important information about the two- or three-dimensional nature of the fractures within the surrounding bedrock. Thus, for instance the problem of contamination of boreholes by performing pumping or injection tests in order to determine suitable water chemistry sampling points, can be avoided by using a combination of these two methods.

4.3 GEOHYDROLOGICAL CHARACTERIZATION

The geohydrological characterization made within the Fracture Zone Project was concentrated on Zone 2 and the hydraulic interaction between Zone 2 and the surrounding bedrock. The following methods were applied:

- Piezometric measurements
- Single hole hydraulic tests in different scales
- Interference tests

- Groundwater flow measurements
- Tracer tests

In addition some special studies were made concerning the amounts of drilling debris being injected into the fractures during drilling and possible influence on hydraulic and transport parameters of this contamination. This is further discussed in Chapter 4.4.

4.3.1 Piezometric Measurements

The purpose of piezometric measurements is to obtain data on the natural head distribution in an area. At the Brändan area, no such measurements had been made in the site characterization programme. Therefore, during the first phase of the Fracture Zone Project, equipment for piezometric measurements was installed in boreholes KFI05 and KFI06. In the detailed characterization phase, also boreholes KFI07, KFI09, KFI10, and KFI11 were instrumented. The equipments used are thoroughly described in Almén et al. (1983) and Almén et al. (1986), see also Figure 4-6. The same type of equipment was also used for monitoring of heads during different hydraulic events such as drilling and interference tests.

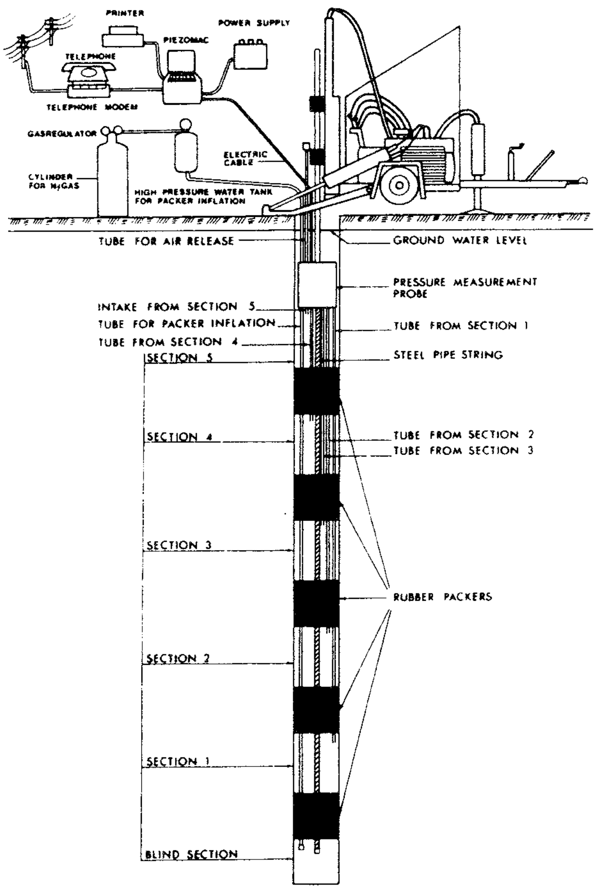


Figure 4-6. Equipment for piezometric measurements /Ahlbom et al., 1986/.

Based on existing data from core logging, geophysical logging and previously performed water injection tests, three to five sections in each borehole were chosen for piezometric measurements. The aim was to isolate different hydraulical units from each other with special emphasis on Zone 2. The results of the measurements are described in Ahlbom et al. (1986) and Ahlbom et al. (1988).

The piezometric measurements resulted in isoelevation maps at three different levels in the Brändan area; above, within, and below Zone 2. The few number of measurement points (4–9), the spatial distribution of the points, and the uncertainties mentioned below made the interpretations somewhat speculative. However, the maps indicate a low hydraulic gradient of about 0.3 % and a direction of the groundwater flow towards east, i.e. approximately opposite to the dip direction of Zone 2.

The measurements revealed several problems which can be separated into two categories; instrumental and interpretational problems. Both categories of problems became rather difficult to handle due to the flat topography with low gradients and hence, small head differences between the sections and boreholes. The most serious instrumental problem was a systematic malfunction in the down-hole probe resulting in a total breakdown of the system after only a short period of measurements. The reason for this was that the equipment had not been tested under field conditions before the start of this project. From this followed that the interpretation of the measurements became difficult due to the many changes of equipment. On top of this, a transducer drift varying with time further complicated the interpretation. However, it should be noted that the concept of using only one pressure transducer to monitor all sections of a borehole has advantages, e.g. easier calibration. The technical problems with the equipment have been solved since the Fracture Zone Project and it has since then been used regularly.

Problems related to the interpretation of the measurements were partly related to the low gradient of the area where head differences were close to the measurement resolution. The most serious interpretational problem came from the presence of saline water. Therefore, in order to compare different pressures to get an idea of the gradients and flow distributions, the measured pressures had to be corrected for the actual salinity in the measured section. To do this, the salinity, or rather the density, has to be measured or determined in some other way. In this project, this was achieved in two ways; by using a salinity log (see Chapter 4.2.2) and by water sampling and subsequent determination of density at the laboratory. Ahlbom et al. (1988) made a thorough investigation of the problem and found that obtaining a correct density value was complicated. The salinity log has a low resolution for salinities above 6 000 ppm (equivalent NaCl) whereas the groundwater sampling reveals concentrations up to 10 000 ppm in the deeper parts of some boreholes. A second difficulty is to translate concentration into density as the density also is dependent on the ion composition as well as the temperature and pressure of the water. Thirdly, the salinity distribution obtained in an open borehole may not be the same as in a packed off borehole.

Ahlbom et al. (1988) used the absolute pressure differences obtained in an open borehole as a measure of the total potential at the different levels. This method was considered to give good estimates of the potential distribution along the borehole. There is also a thorough discussion about why the saline water not rises above the upper part of Zone 2 and it is concluded that this is an effect of the high contrast in hydraulic conductivity between the upper part of Zone 2 and the overlying rock. Finally, Ahlbom et al. (1988) discusses the possibility that changes in the piezometric conditions may occur due to the long period of open hole conditions prior to isolation of the boreholes with packers. Short-circuit effects may have interconnected zones of different salinity which slowly will stabilize.

The conclusions that can be drawn from the piezometric measurements in a system like Finnsjön with waters of different density are the following;

- the density of the water in the measurement section has to be determined in order to obtain gradients and flow distribution

- determination of density from salinity logs alone is not sufficient

- density of the water should be determined by sampling or, if only one pressure transducer is used for monitoring all sections of a borehole, the pressure difference determined between the different levels in an open borehole

- small changes in the piezometric conditions with time occur during the measurement period but it might be difficult to judge whether this is an effect of previous short-circuiting effects or an effect of other external factors such as precipitation and tidal effects.

Finally, the piezometric measurements including registration of other hydraulic disturbances, such as drilling, have proven to give substantial information regarding interconnectivity of fracture zones. This was illustrated during the drilling of borehole BFI01 /Ahlbom et al., 1988/ and during drilling of HFI01 /Ahlbom et al., 1986/ where hydraulic connections between HFI01 and KFI05 at two different levels could be identified, one of them being Zone 2, see Figure 4-7.

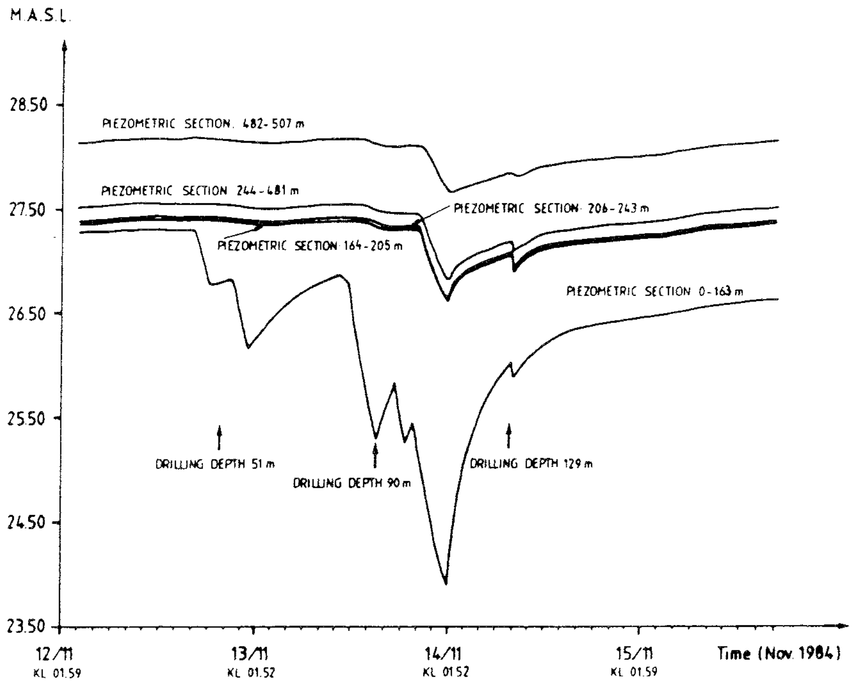


Figure 4–7. Piezometric registrations in KFI05 during drilling of HFI01 /Ahlbom et al., 1986/.

4.3.2 Single Hole Hydraulic Tests

A large number of single hole hydraulic tests have been made within the Fracture Zone Project with the objective to characterize the bedrock within and around Zone 2. In addition, some special tests have been performed with the following objectives:

- to test equipment and procedures for hydraulic tests in extremely short (0.11 m) intervals /Andersson et al., 1988/
- to compare tests performed with different equipment systems /Andersson et al., 1987/
- to study the effects of gas–lift pumping on borehole hydraulic parameters /Andersson et al., 1987, 1991/

The testing strategy for this project differs somewhat compared to that used in earlier site characterization. Instead of measuring all boreholes from top to bottom in 3 m intervals, more detail was brought to Zone 2 and less to the surrounding rock. Another difference is the use of different scales of measurement in the same borehole. The large number of tests, the detailed scales, and the spatial distribution of the tests made it possible to make comparisons of results from tests in different scales, geostatistical analyses and perform stochastic modelling using hydraulic conductivity values determined from single hole hydraulic tests. The test designs and results are given in Ahlbom et al. (1986), Ahlbom et al. (1988), Andersson et al. (1988), Ekman et al. (1989), and summarized in Andersson et al. (1991).

The tests in 0.11 m sections were applied in borehole BFI02 with the aim of determining the "hydraulic width" of the most high-conductive parts of Zone 2. Totally 8 m of the zone was tested and the results (Figure 4-8) indicate that the high transmissive parts are only about 0.3-0.5 m thick in the three subzones tested /Ekman et al., 1989/, /Andersson et al., 1989a/. The test design and equipment worked well but corrections for frictional losses in the equipment may be required for the highest flow rates.

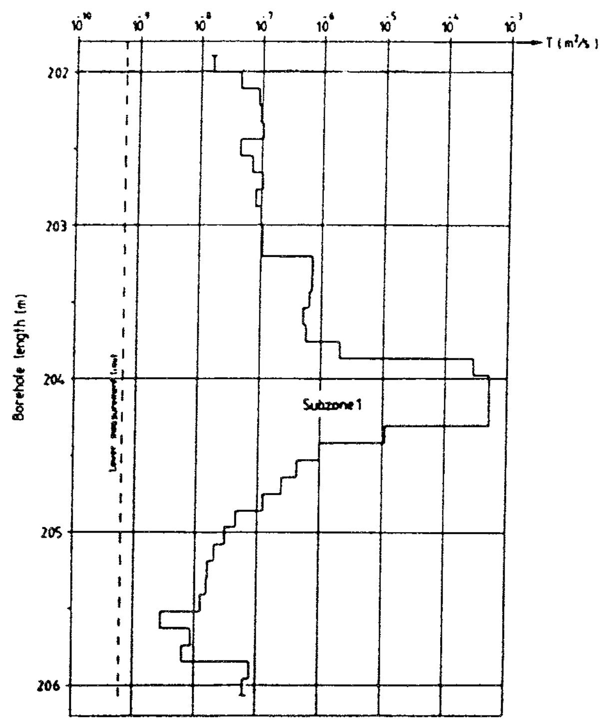


Figure 4-8. Transmissivity distribution of the uppermost subzone of Zone 2 in 0.11 m sections in borehole BFI02 /Andersson et al., 1989a/.

A comparison of equipment systems was made by performing exactly the same measurements in the same borehole intervals in borehole KFI10 using two different measurement systems, the Umbilical Hose System and the Pipe String System. Both systems are described in Almén et al. (1986). The results of the tests, presented in Andersson et al. (1987), were:

- the practical upper measurement limit for both equipments was estimated ($T = 10^{-5}$ m^2/s for the Umbilical Hose and $T = 2 \cdot 10^{-5}$ m^2/s for the Pipe String)

- the hydraulic conductivity values calculated from the tests were in good agreement, see Figure 4–9.

- it is important to consider the length error due to elasticity in the load carrying wire when using the Umbilical Hose System

The last point is illustrated by the section 210–230 m in Figure 4–9 which falls completely outside due to a depth determination without taking the length error into account.

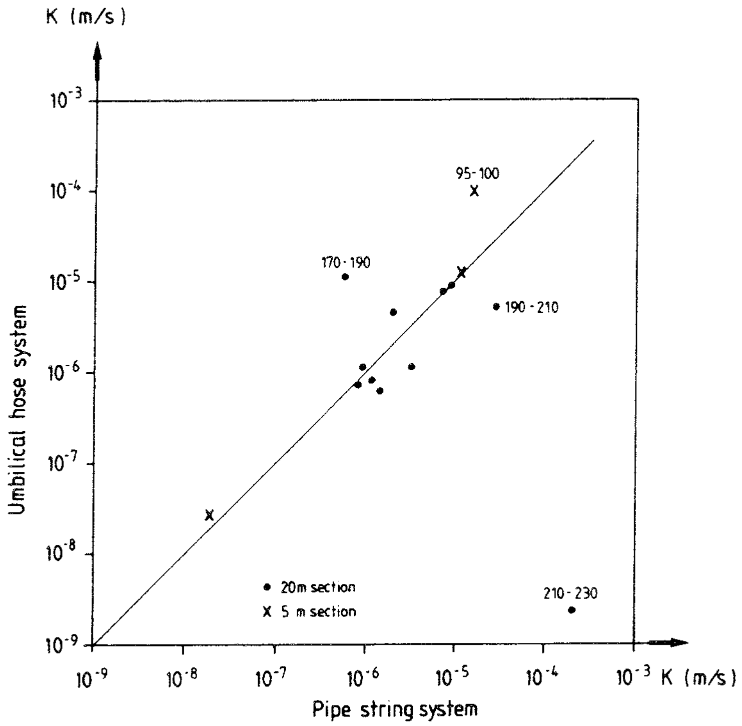


Figure 4–9. Cross–plot of hydraulic conductivity calculated from tests with the Umbilical Hose System and the Pipe String System /Andersson et al., 1987/.

Gas–lift pumping is made in order to clean the borehole from drilling debris, drilling water, and drill cuttings. The pumping is in general performed shortly after drilling of the borehole. The investigation showed that less than 1% of the remaining drilling debris was recovered by gas–lift pumping in cored boreholes /Andersson et al., 1989a/. Thus, large amounts of drilling debris is likely to have been injected into the bedrock, c.f. Chapter 4.4. Single–hole hydraulic tests were performed with the same equipment and in the same intervals prior to and after the gas–lift pumping. The results showed no significant difference between the two measurement sequences neither on conductivity values nor on calculated skin factors. Consequently, the gas–lift pumping seemed to have a very limited effect as a means of cleaning boreholes from drilling debris .

4.3.3 **Interference Tests**

Hydraulic interference tests are performed mainly to determine hydraulic properties averaged over some distance and to study the heterogeneity and anisotropy of the rock. In the Fracture Zone Project also the connectivity of fracture zones, in particular Zone 2, was confirmed by using interference tests. Several interference tests were performed with observations as far as 1500 m from the pumping well. Besides the more common method of pumping an entire borehole, some new methods were successfully tested. The methods used within the Fracture Zone Project were;

- gas–lift pumping (entire borehole)
- gas–lift pumping between packers
- air–flush pumping during percussion drilling
- conventional pumping from isolated intervals of Zone 2

The gas–lift pumping is, as mentioned above, normally used to clean the boreholes from drilling debris. In the earlier site investigations no attempts were made to use the gas–lift pumping as an interference test, mainly due to the uncontrolled flow. Another problem is the small borehole diameter, 56 mm, which, in practice, makes it impossible to use downhole mechanical pumps. However, within the Fracture Zone Project, a modified gas–lift pump equipment was tested, see Figure 4–10. One test without packers and two tests within an isolated borehole section were made in borehole KFI09 /Ahlbom et al., 1986/.

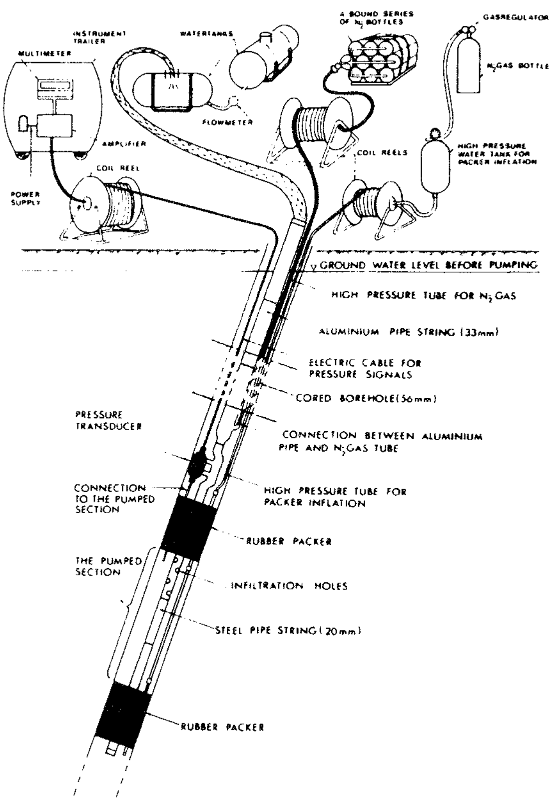


Figure 4–10. Equipment for gas–lift pumping between packers /Ahlbom et al., 1986/.

The method was shown to work well giving discharge rates high enough for monitoring drawdowns at several hundred meters from the pumping well. It was also possible to keep a sufficiently constant discharge rate to enable evaluation applying methods used for constant flow tests. The possibility to pump a small diameter borehole between packers is a major improvement of the method. Thereby, the method is more applicable in the Swedish site characterization programme with small diameter cored boreholes.

During the drilling of percussion boreholes, compressed air is continuously flushed into the borehole in order to clean it from drill cuttings and drilling debris. During the drilling of the percussion boreholes HFI01, BFI01 and BFI02 this air-flush pumping was also used as a method for performing large scale interference tests. Early in the project, when drilling the water supply well HFI01, the pumping effect created by the air-flushing was used in a qualitative way to study the pressure responses in some of the adjacent boreholes /Ahlbom et al., 1986/. In fact, this was the first indication of the presence of Zone 2, although interpreted as Zone 1 at that time.

The main test of the method was made in conjunction with the drilling of borehole BFI01. This borehole was drilled according to a new concept: step by step drilling with subsequent groundwater sampling and interference tests. The advantage of this method is that it permits the location of hydraulically conductive features fairly precisely and obtaining representative groundwater samples at each level before continued drilling and subsequent contamination of the sampled section, c.f. Chapter 4.4. In total, five interference tests were performed at different drilling steps. Pressure responses were registered using the same equipment setup as described in Chapter 4.3.1. The results of the tests showed that the method can add valuable information of the hydraulic conditions at an early stage in a project. However, since drilling was the primary interest, all circumstances for a satisfactory quantitative interpretation of the tests could not be accomplished. The earlier mentioned problems with the piezometric monitoring system made part of the interpretation difficult, but much valuable information regarding the hydraulic properties of Zone 2 and the surrounding bedrock was gathered, c.f. Chapter 5. The tests also revealed some problems related to the interpretation as well as to the performance of the tests. The main problems were:

- short duration of the tests (1–13 hours) made it difficult to draw definite conclusion regarding hydraulic boundaries

- large flow rate variations in the pumphole

- no registration of the drawdown in the pumphole

- extremely rapid pressure propagation within Zone 2 demanded a better (more dense) pressure registration

The last problem was not expected, but due to the performance of these tests, a good basis for the design of the subsequent large scale interference tests in isolated sections of Zone 2, could be made.

The large scale interference tests performed within the Fracture Zone Project were the first large scale tests performed in Sweden in crystalline bedrock where a sectionized borehole was used as pumping well in combination with multiple-well, multiple-section monitoring of the pressure responses. The primary objective of the large scale interference tests was to determine hydraulic properties and boundaries of Zone 2 and subzones of Zone 2 and also to investigate the connectivity of the subzones. The tests are thoroughly described in Andersson et al. (1989a).

The tests were performed in three steps, the first two by pumping in the two most highly conductive sections of Zone 2, and the third by pumping the entire thickness of Zone 2, see Figure 4–11. The test design applied permitted experiences from the problems with the performance and interpretation of the air-lift tests described above to be considered. Thus, pressure monitoring was carried out in much denser time intervals, at least two packers were used to isolate each monitoring section from each other to avoid short-circuiting effects, and monitoring was made as far away as 1500 m from the pumping well (BFI02).

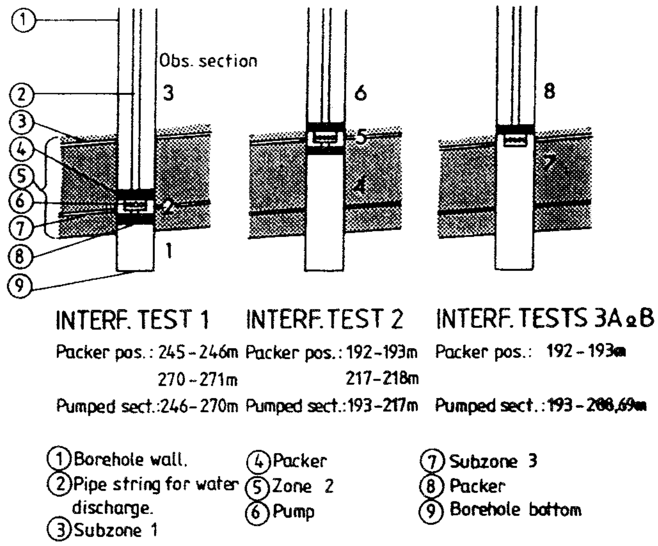


Figure 4–11. Schematic illustration of the experimental design in the pumping hole BFI02 during the large scale interference tests /Andersson et al., 1989a/.

The interference tests made clear that the upper part of Zone 2 is highly conductive and interconnected over hundreds of meters in the lateral direction and that the zone is bounded by other fracture zones.

The results of the series of interference tests performed within the Fracture Zone Project clearly demonstrated the usefulness of conducting such tests by pumping and recording pressure in multiple borehole sections. The successful performance of the tests showed that the technical design of the system was good and should be repeated in the future. Another special feature of these investigations was the combination of interference test with tracer test performed in one of the pumpings. This appeared to be very successful and is highly recommended for the future, c.f. Chapter 4.3.5. Finally, monitoring of independent parameters such as electrical conductivity and temperature of the pumped water gave substantial information regarding interconnectivity of the subzones within Zone 2. By extending this further, incorporating other chemical parameters, further knowledge about the connectivity and boundaries of the system may be achieved.

4.3.4 Groundwater Flow Measurements

With the point dilution technique a semi–quantitative method for in situ measurements of groundwater flow rate under natural or induced hydraulic gradient is provided. Within the Fracture Zone Project, this method was used for the first time with the purpose of actually determining flow rates in boreholes and sections of boreholes. Earlier measurements performed in Sweden were aimed at developing the equipment and testing the theories in crystalline bedrock /Gustafsson, 1986/. The method relies upon the fact that the dilution of a chemical substance added to a borehole or a section of a borehole is directly proportional to the flow through the borehole/section.

Two boreholes, HFI01 and BFI01, were measured under natural gradient conditions in packed off sections both within and outside Zone 2 /Andersson et al., 1989a/. In addition, groundwater flow rates under induced gradients were determined during the radially converging and the dipole tracer tests /Gustafsson and Nordqvist, 1993/, /Andersson et al., 1993/. The measurements were made using two different concepts, one with a down–hole instrument and the other by circulation of tracer between the ground surface and a borehole section. In the second method sampling and subsequent laboratory analyses are made to determine the dilution of tracer versus time. Both methods were shown to work well in crystalline rock. The flow measurements were able to confirm the hydrochemical indications that the natural gradient in the lower parts of Zone 2 is very low, or even stagnant. The investigations in borehole BFI01 also involved flow measurements in a 180 m long section above Zone 2 using the sampling method. The successful performance of this test at Finnsjön made it possible to plan for and utilize the method more by routine in the preinvestigation phase at the Äspö Hard Rock Laboratory.

The flow measurements performed under induced gradient were used as input parameters (source term) for the tracer injections during the two large scale tracer tests performed within the project, c.f. Chapter 4.3.5.

4.3.5 Tracer Tests

One of the main objectives of the Fracture Zone Project was to study the flow and transport characteristics of Zone 2. Therefore, a number of different tracer tests were suggested both for determination of the transport characteristics and for the development of tracer test methodologies in highly conductive rock. Another important objective of the tracer tests was to verify and, if possible, validate models describing radionuclide transport, c.f. Chapter 5. A series of three large scale tracer tests were designed to meet these objectives /Gustafsson et al., 1987/:

- radially converging tracer test
- dipole tracer test
- natural gradient tracer test

The original intention was that the first two tests should give the necessary input of transport parameters to the transport model, and the natural gradient test should provide the verification/validation. Unfortunately, the natural gradient test could not be realized for various reasons, mainly lack of time and resources.

Before these tests were performed, several other tracer tests were used at various stages of the project for specific purposes, e.g. to support the planning of the three main tests:

- transport of labelled drilling fluid (three tests)
- transport of labelled injection water during single hole hydraulic tests
- tracer test in combination with interference test
- test of short-circuiting effects around packers
- test of delay and dispersion in pump hole and sampling equipment
- tracer dilution tests, see also Chapter 4.3.4

The performances and methodologies applied during most of the tests within this project were new and unique. Below, a brief summary of each test is given, highlighting the benefits and disadvantages of the respective method.

4.3.5.1 Transport of Tracer Labelled Water during Drilling and Hydraulic Testing

The first tracer method applied within the project was to study the transport of labelled drilling fluid during the drilling of boreholes KFI09, KFI10, and KFI11. The main objective of the method is to study possible interconnections between the borehole being drilled and adjacent boreholes, in this case the drilling water supply well, HFI01. In addition, pressure responses caused by the drilling were monitored, c.f. Chapter 4.3.1.

During the first test, the drilling of borehole KFI09 /Ahlbom et al., 1986/, the drilling supply well was pumped intermittently, 5 m^3 at each cycle, which was the normal procedure during drilling. However, in order to get a better control of the hydraulic conditions, a constant pumping of the water supply well was applied during the drilling of borehole KFI11 /Ahlbom et al., 1988/. The results of the three studies of labelled drilling fluid clearly demonstrate the usefulness of the method. Clear evidence of hydraulic connections between the boreholes could be determined at a very early stage of the investigation. Also, the transport between boreholes KFI11 and HFI01, over a distance of 440 m, is one of the largest scales of a tracer test ever performed in crystalline rock.

The latter test displays a very smooth breakthrough curve (Figure 4–12) with a mean travel time of 37 days. The breakthrough data could also be used for rough estimates of transport parameters such as flow porosity and fracture apertures /Ahlbom et al., 1988/, /Gustafsson & Andersson, 1991/. The main problem associated with these estimates is the lack of control of the injection as the drilling fluid is unevenly injected with high pressure during the drilling. The radius of influence for the drilling was estimated to 30–60 m assuming a homogeneous spreading of the injected fluid, which is not likely to be the case /Ahlbom et al., 1988/. However, due to the large distance and evidently good mixing the highly irregular injection has smoothened out to a nice pulse at HFI01 (Figure 4–12). Hence, the use of labelled drilling fluid as a tracer has shown to add substantial information regarding the connectivity of Zone 2, to a minimum of cost. The test also provided good information for the planning of the forthcoming tracer tests.

Tracer labelled water was also used for the single–hole injection tests performed in borehole KFI10 /Ahlbom et al., 1988/. Also in this case tracer transport to the continuously pumped borehole HFI01 could be detected.

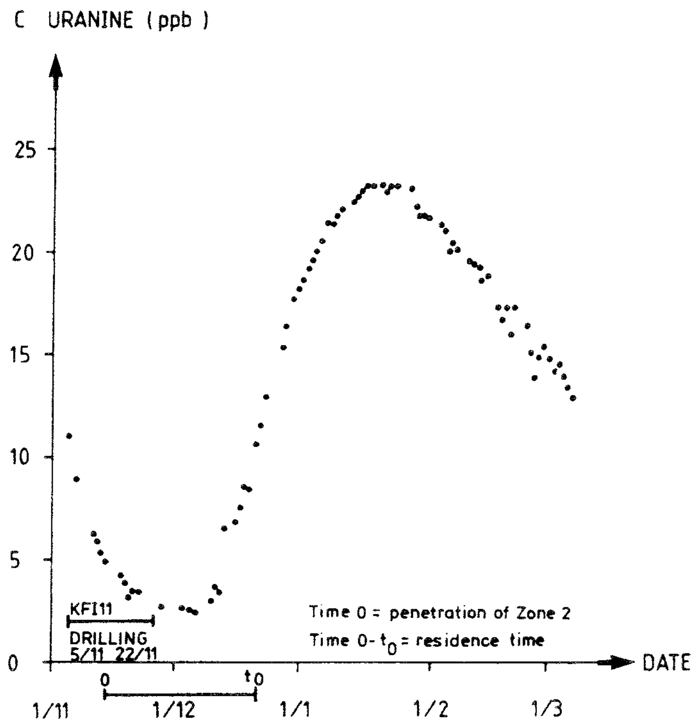


Figure 4–12. Breakthrough of tracer labelled drilling fluid in borehole HFI01. The initial occurrence of Uranine is due to earlier tests /Gustafsson & Andersson, 1991/.

4.3.5.2 Tracer Tests in Combination with Interference Test

In order to optimize the design of the radially converging tracer test, the first of the three planned large scale tracer tests, a preliminary tracer tests was performed during the one of the large scale interference tests /Andersson et al., 1989a/. The main objective of the test was to determine the hydraulic connectivity within what was considered to be the upper highly conductive part of Zone 2. Ideally, tracer transport parameters should be able to be determined as well. The difficulty associated with the test was mainly the injection procedure, which ideally should be performed without disturbing the pressure registration in the injection section. The test was performed by injecting three different tracers in three boreholes at distances of 155–189 m from the pumping borehole BFI02. The injections were made in packed-off sections of the upper highly conductive part of Zone 2, see Figure 4–13.

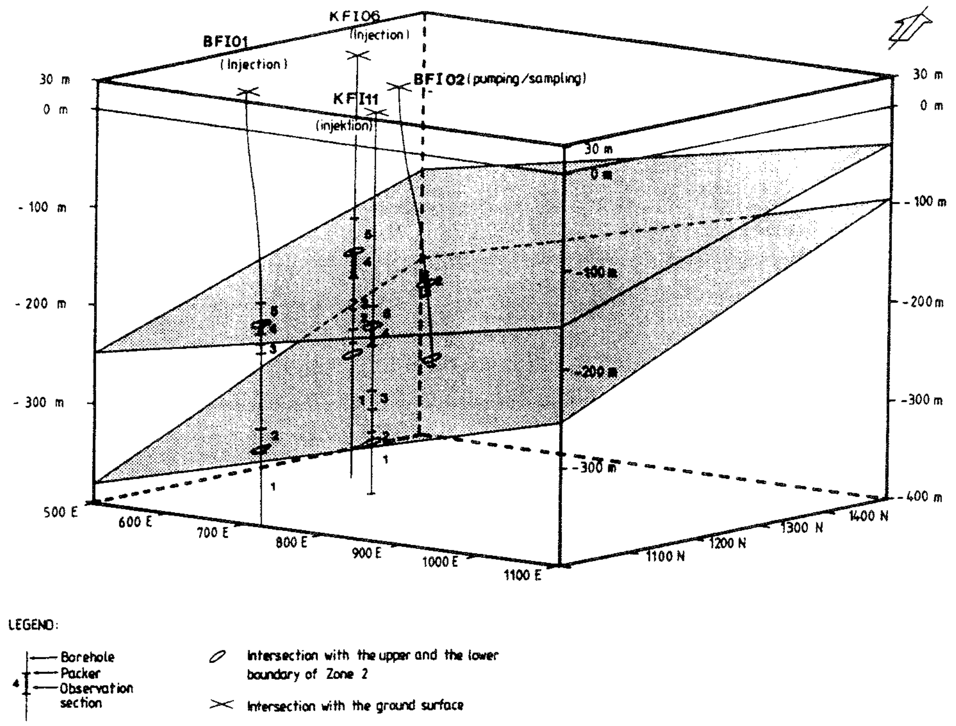


Figure 4–13. Three-dimensional block diagram showing the positions of the boreholes used for the pulse injection of tracers in the interference test /Gustafsson & Andersson, 1991/.

To overcome the problem with simultaneous injection of tracer and undisturbed pressure, the injection was finished before starting the interference test. Due to the high transmissivity of the zone, pressures were stabilized within minutes. A disadvantage of using this procedure was that transient flow and head conditions were prevailing during the transport of tracers. However, head measurements showed that within 10 minutes an approximate steady-state was reached /Gustafsson & Andersson, 1989/. Hence, a number of different transport parameters could be determined such as hydraulic fracture conductivity, fracture apertures, flow porosities, and dispersivities. All parameters were determined in three different directions giving information regarding the heterogeneity of Zone 2. Comparison of parameters determined from this test and the radially converging test performed in the same geometry shows very similar values of the transport parameters, c.f. Chapter 5.

The tracer test performed in conjunction with the interference test added substantial information regarding transport parameters and connectivity in Zone 2. The method is highly recommended to use in future investigations.

Subsequent to the above described tracer test, a test of possible short-circuiting effects in the pumping borehole was conducted. The test was made by injecting a small pulse of tracer immediately below the lower packer during one of the interference tests. The results showed that no tracer was detected in the discharged water during the interference test, while all of the tracer was recovered after removing the packer. The method was shown to be simple to apply and to work well /Gustafsson & Andersson, 1991/.

4.3.5.3 Radially Converging Tracer Test

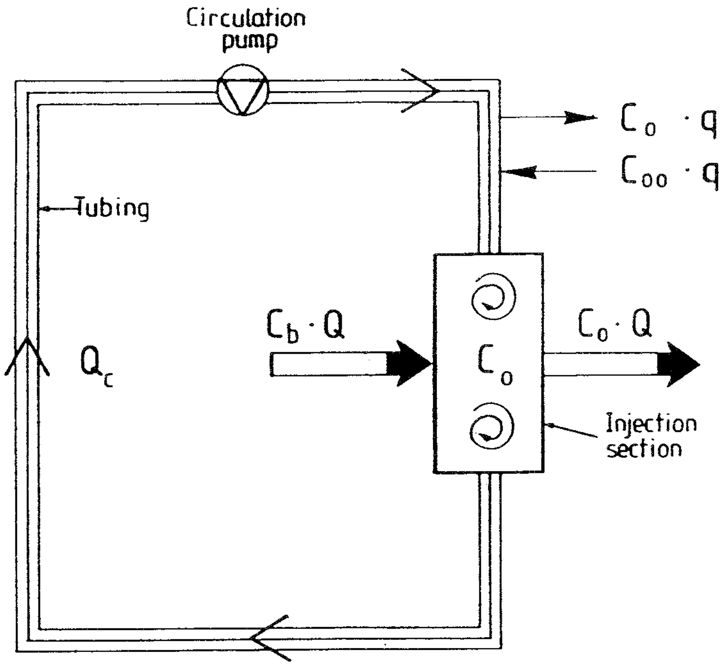
The radially converging tracer test was performed with the main objective to determine transport parameters of Zone 2. All available geologic, geophysic and hydraulic information indicated that Zone 2 consisted of 2–6 highly conductive subzones with relatively low conductive rock in between. Therefore, it was decided to inject tracers in three different subzones of Zone 2. The test was performed by pumping in borehole BFI02 and injecting tracers in boreholes KFI06, KFI11, and BFI01. The test design is described in Gustafsson et al. (1990) and the evaluation of the test in Gustafsson & Nordqvist (1993).

The unique features of this test compared to other converging tests performed in crystalline rock were:

- multilevel injection in multiple boreholes (nine injection points)
- continuous injection without applying excess pressure or creating dispersion in the injection system
- use of stable rare earth metal complexes as tracers
- multilevel sampling of tracers in the pumping borehole

The introduction of so many new methods was made possible due to a supporting research program where tracers and injection/sampling methods where tested prior to the actual tracer test. Tests of equipment for injection and sampling of tracers were made both in laboratory and in field /Andersson et al., 1988/. The rare earth metal complexes (EDTA and DTPA–complexes) were subject to comprehensive tests including stability, solubility, sorption and interference effects /Gustafsson et al., 1990/. The tests also included analysis of water samples from Zone 2 for determination of natural background concentrations of the tracers.

Ideally, the shape of a tracer breakthrough curve should only reflect the processes in the fracture system. However, in many earlier performed tracer tests injection of tracer has been performed simply by flushing an arbitrary volume of tracer into the injection borehole or by continuously injecting a tracer solution into a borehole section where uncontrolled mixing with the native water occurs. These procedures may seriously affect the shape of the breakthrough curves, giving dispersive effects or loss of tracer into stagnant zones. Therefore, a very careful injection and sampling procedure was regarded as necessary for the radially converging tracer test. The injection system was designed to minimize the delay and dispersion by using the natural, or induced, groundwater flow (Q_w) to carry away the tracer, i.e. no excess pressure was applied, see Figure 4–14. There are two other advantages with the system, firstly that the groundwater flow rate through the borehole section can be indirectly monitored as the dilution of tracer is directly proportional to the flow, secondly that the system enables simultaneous injection and sampling, the later being applied during the dipole tracer test /Andersson et al., 1990/.



Q = Groundwater flow rate
Q_c = Circulation flow rate
q = Tracer injection flow rate
C_o = Tracer concentration in injection section
C_{oo} = Initial tracer concentration
C_b = Background concentration of tracer

Figure 4–14. Schematic of the injection and circulation system used for the radially converging tracer test /Gustafsson et al., 1990/.

The success of the injection procedure relies upon the fact that the tracer solution is homogeneously distributed in the borehole section. This is achieved by a pump continuously circulating the water in the injection section and tubing system with a pumping rate Q_c. This circulation flow should ideally be much higher than the groundwater flow in order to achieve a good mixing.

Before starting the injection, the groundwater flow rate Q_w is determined by adding a small amount of concentrated tracer solution ($C_{00} \cdot q$) to the mixed system. In order to quickly achieve a homogeneous solution the duration of this injection is exactly the time it takes to circulate one borehole volume. When Q_w has been determined, the initial tracer concentration (C_{00}) needed can be determined. The tracer injection is then started in the same way. The same volume per time unit as injected is also discharged in order to avoid pressure buildup. By measuring the tracer concentration in the discharged water (C_0), the flow rate can be determined throughout the entire injection procedure /Gustafsson et al., 1990/.

The results of the radially converging test show that the technical part of the injection system still need to be developed. Several injection stops occurred due to degassing of the tracer solution in the storage tanks and gas bubbles being trapped in the pump heads. Pump stops also occurred due to power failures. Another problem was variations in the flow rate through the borehole sections, in most cases a decreased flow rate which may be an effect of chemical clogging.

The new sampling procedure used involved a detailed sampling of 7 different 2 m–intervals of Zone 2. The sampling was carried out towards the end of the test, when tracer breakthrough in most sections had reached steady state. The results indicated a complex flow pattern within Zone 2 with several interconnecting flow paths between the upper and lower parts of Zone 2. An example is given in Figure 4–15, where the tracer ReO_4^-, injected in the lower part of Zone 2, was found both in the lower and in the upper parts of the zone.

In summary, the results of the radially converging test demonstrate that the method is well suited for transport characterization of major fracture zones. The new methods for injection and sampling are good improvements but still need some minor modifications to work entirely satisfactory. Finally, the rare earth metal complexes tested, measurable in extremely low concentrations, seem to be highly applicable as conservative tracers in large scale tracer tests.

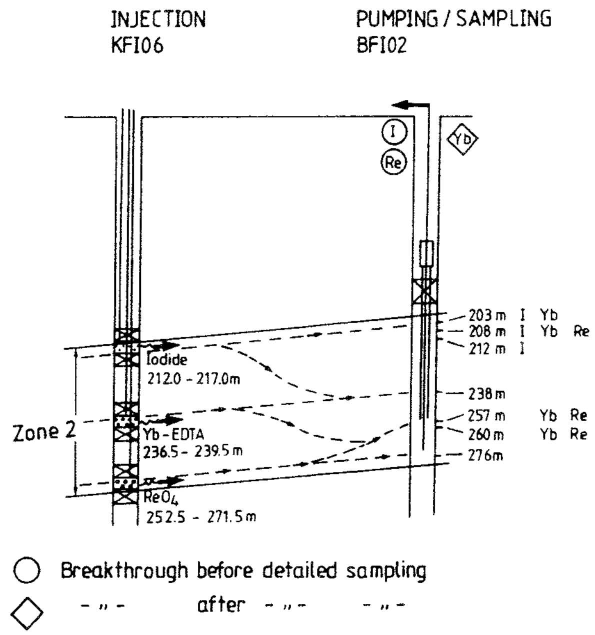


Figure 4–15. Illustration of results from the detailed sampling in BFI02 /Gustafsson et al., 1990/.

4.3.5.4 Dipole Tracer Test

The second large scale tracer test, the dipole tracer test, was performed with the objective to obtain transport parameters in the same borehole geometry as in the radially converging test but with a different flow geometry. This enabled a direct comparison between the two tests. In this test only the upper highly conductive part of Zone 2 was pumped using a recirculating system where the water pumped from borehole BFI02 was recirculated through plastic tubing into borehole BFI01, see Figure 4–16. The test design is described in Andersson et al. (1990), and the evaluation in Andersson et al. (1993).

The dipole tracer test is the first of its kind performed in Sweden. There are also some other special features of the tests:

- use of short–lived radioactive tracers
- continuous control of redox potential (Eh) and electrical conductivity
- observation boreholes within the dipole flow field with undisturbed monitoring of tracer breakthrough
- tracer injection in observation borehole with simultaneous sampling

The introduction of short–lived radioactive tracers required a very careful testing of tracers and a rigorous handling using authorized personnel from the Department of Nuclear Chemistry, Chalmers, Göteborg.

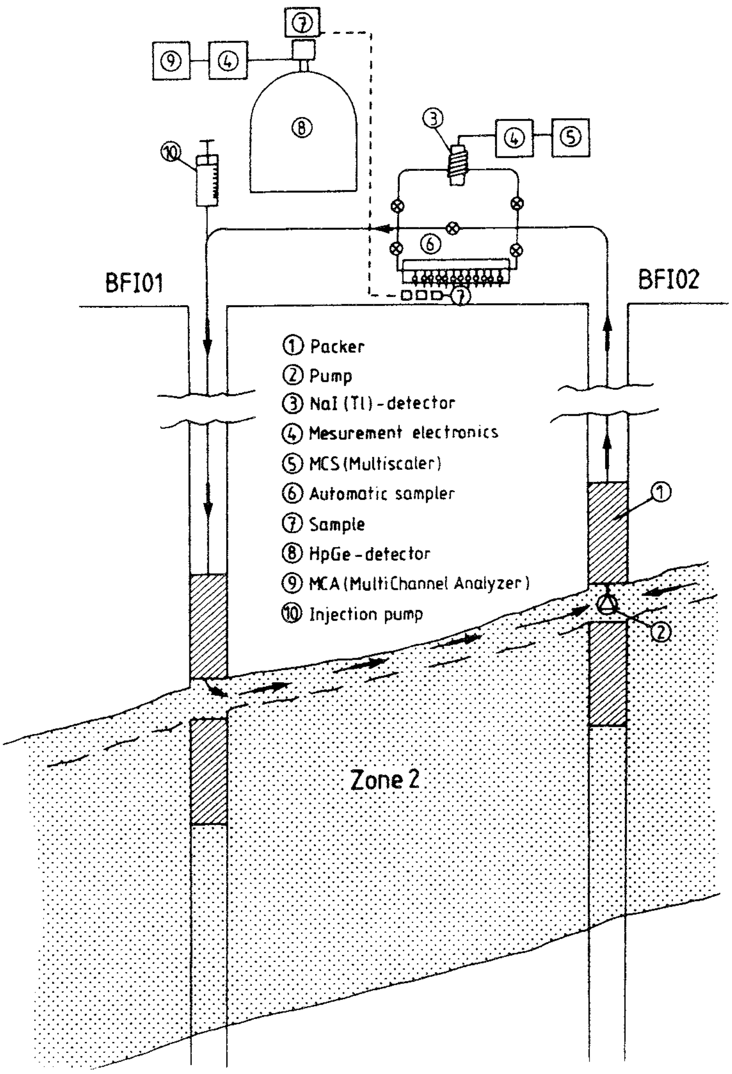


Figure 4–16. Experimental design of the dipole tracer test /Andersson et al, 1993/.

In total 14 different radioactive and 5 non–radioactive tracers were used during the one month duration of the dipole tracer test. The test also involved both sorbing and non–sorbing tracers. The results of the tests using short–lived radioactive tracers showed that these are possible to use in large scale field tests /Byegård & Skålberg (ed.), 1992/. The major advantages are that very fast and simple analyses may be done in situ and that the tracer will disappear totally by time. However, this may also be regarded as a disadvantage, as the short half–lives of the tracers also requires fast analyses which puts high demands on the analysis equipment and personnel.

The test also involved injection of technetium–99 as pertechnetate (TcO_4^-). Technetium in the form of pertechnetate is very soluble and has a low sorption on rock mineral surfaces. Under oxidizing (air) conditions technetium will form pertechnetate. However, laboratory experiments indicate that pertechnetate will become reduced to tetravalent Tc(IV) under normal reducing deep groundwater conditions /Eriksen & Cui, 1991/, /Byegård et al., 1992/. This was confirmed by the in–situ experiments at Finnsjön. The redox potential monitored during the experiment showed stable reducing conditions and no breakthrough of Tc-99 was registered despite the fact that it was injected as pertechnetate. This can only be explained by an in-situ reduction of mobile TcO_4^- to immobile Tc(IV) /Byegård et al., 1992/. Natural geochemical conditions at depth in granitic rock will therefore act as a barrier against technetium dissolution and migration. Until the Finnsjön experiment, this has only been indicated by laboratory experiments where it is difficult to simulate reducing conditions.

The use of observation boreholes within the dipole flow field was efficient for adding information about the heterogeneity of the system. The system with constantly mixed observation intervals, as described in Chapter 4.3.4, made it possible to obtain breakthrough data of high quality in these boreholes. Another advantage was that the time scale of the experiment expanded. Instead of one breakthrough curve with mean travel times of 45 hours, three curves having mean travel times of 20–200 hours were obtained. However, for some of the tracers only one or two breakthroughs could be monitored due to the short half-lives of the radioactive tracers. One of the observation boreholes, KFI11, was also used for tracer injection, using this "undisturbing" system.

In summary, the dipole tracer test demonstrated the possibility and the advantages of using short-lived radioactive tracers in large scale field tests. Also, the value of having observation boreholes within the flow field was clearly demonstrated. This may be even more interesting in small scale tests, where drilling costs are comparatively small. Finally, the test may certainly be applied in the characterization of fracture zones, but due to the large spreading of the flow field, tracer losses may occur and thereby create an uncertainty and loss of control of the test. Therefore, radially converging tests are preferred to use for characterization of major fracture zones.

4.4 GEOCHEMICAL CHARACTERIZATION

The geochemical characterization of a site is necessary for understanding and estimating processes influencing the amount of radioelement transported by the groundwater and also to estimate the integrity towards corrosion and chemical changes of materials used in a repository /Puigdomenech & Nordstrom, 1987/. The geochemical characterization of Zone 2 and the surrounding bedrock specifically aimed at studying the chemical evolution of the groundwaters within and around Zone 2. Particular emphasis was given to redox-sensitive parameters, stable and radioactive isotopes and the chemical and radiochemical behavior of uranium. This was accomplished by chemical analyses of water and rock from the boreholes at the site. The results are reported in Ahlbom et al. (1986), Puigdomenech & Nordstrom (1987), Smellie et al. (1987), and Smellie & Wikberg (1991).

The hydrochemical characterization of Zone 2 and the surrounding bedrock only constituted a minor part of the overall programme. Besides the conventional water sampling programme also some new ideas and methods that may aid to improve the quality and representativity of the water samples have been applied. Past experience has shown a serious lack of representative groundwater samples for hydrochemical characterization /Smellie et al., 1985/. Smellie & Wikberg (1991) discuss a number of different sources of disturbances to the groundwater quality coupled to the drilling and testing of the borehole. Also, the natural pressure distribution within the borehole may cause water to flow along an open borehole with contamination as a consequence. The extent of drilling debris as a potential groundwater contaminant is largely unknown. Smellie & Wikberg (1991) suggest that this may be the case, e.g for studies of colloids and uranium where ionic complexes may become bound on the debris particles and subsequently removed during filtration. Within the project, studies of the amounts of drilling debris and drilling water injected into the fracture system during the drilling was measured during drilling of KFI09, KFI10, KFI11, BFI01, and BFI02 /Ahlbom et al., 1986/, /Ahlbom et al., 1988/, /Andersson et al., 1991/. The results of these measurements clearly indicate that large amounts of drilling debris and drilling water remains in the borehole after drilling and cleaning, see also Chapter 4.3.2.

To improve the quality of groundwater sampling a new technique was suggested and tested as a part of the Fracture Zone Project. The technique involved air-percussion rotary drilling in a stepwise way with subsequent groundwater sampling (borehole BFI01). This technique would have the advantages of /Smellie & Wikberg, 1991/:

- locating fairly precisely the intersection depth of the hydraulically conductive horizons

- obtaining representative groundwater samples

- avoiding groundwater contamination from open-hole effects

The borehole location was selected to avoid contamination from earlier drilling activities. Therefore, a special analysis of the possible radius of influence of earlier drilling operations was made.

The results of the tests with the new groundwater sampling method demonstrated the limitations with the air-flush percussion drilling technique for water sampling purposes. The technique is only efficient down to relatively shallow depths (200–250 m). Below this depth a considerable air-pressure is needed to clear the borehole from rock debris and water which also extends the radius of contamination due to air intrusion. Long pumping times are therefore necessary to remove these effects. Instead, Smellie and Wikberg (1991) recommend the use of rotary water flush techniques at depths greater than 200–300 m, as smaller water pressures then are required.

A method study concerning the possibility of localizing fracture zones covered by Quaternary deposits by using measurements of radon, methane and helium concentrations was also performed at the Brändan Zone /Lindén et al., 1987/. The investigation showed increased concentrations of radon, methane, and helium over the zone compared to the surroundings.

4.5 ROCK MECHANICAL CHARACTERIZATION

The rock mechanical investigations within the project constituted only a minor part of the programme. The only field measurements performed were rock stress measurements conducted by means of hydraulic fracturing technique in 40 sections of one borehole (KFI06) /Bjarnason & Stephansson, 1988/. The measurements were made above, within, and below Zone 2. The test method worked well technically, although 23 of the 40 measurements were discarded due to either non–ideal test conditions or due to non–vertical fracturing, which made it impossible to determine horizontal stress magnitudes. From the 17 successful measurements, horizontal and vertical stress magnitudes were calculated. A typical hydrofracturing record from KFI06 is presented in Figure 4–17. A special problem with such measurements in fracture zones is to locate a suitable, unfractured section. Consequently, only 2 measurements could be made within Zone 2.

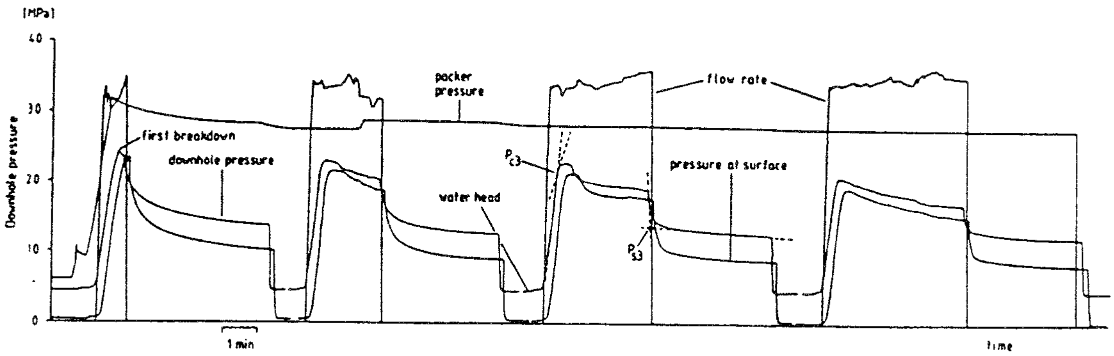


Figure 4–17. Hydrofracturing record from borehole KFI06, 177 m borehole length /Bjarnason & Stephansson, 1988/.

The hydrofracturing method has earlier been applied in the SKB programme at the Gideå site /Bjarnason and Stephansson, 1986/. The method has also been subject to comparison with three other methods /Stephansson et al., 1986/ where regression analysis of maximum and minimum horizontal stresses versus depth were presented. The analysis demonstrated that the hydrofracturing method gave lower stress magnitudes compared to the overcoring technique. The results of the stress measurements are discussed in Chapter 3.1.3.

The rock mechanical characterization also involved determination of the deformational characteristics expressed by the deformation modulus /Leijon & Ljunggren, 1992/. The deformation modulus was calculated in three different ways giving similar results within and below Zone 2, while a larger discrepancy was found above the zone. The estimates were considered to be crude, but still useful to determine bounds for the deformation modulus, c.f. Chapter 3.1.3.

5 MODELLING OF FLOW AND TRANSPORT WITHIN ZONE 2

This Chapter presents an overview of the modelling efforts performed within the Fracture Zone Project and in other projects, INTRAVAL and SKB-91, using data from the project. The modelling is described in this chapter and conclusions regarding flow and transport are given in Chapter 6.2.

5.1 GENERAL

The unique and extensive investigation of the Brändan area and in particular of Zone 2 has served as a good basis for a large number of modelling efforts. These may be divided into three groups based on the purposes of the modelling. They are:

- modelling performed as a part of the Fracture Zone Project with the main objective to determine flow and transport parameters of Zone 2
- modelling performed within the INTRAVAL Project aiming at the validation of different transport models and at developing and testing new modelling concepts
- modelling performed as a part of the SKB 91 study aiming at analyzing the performance of a repository for spent nuclear fuel and how geological and hydrological properties affect the safety analysis.

In this report, only the modelling which was made in connection to the investigations performed within the Fracture Zone Project will be discussed. This means that only a few of the modelling efforts in the SKB 91-study will be included.

An overview of all modelling efforts are presented in Table 5-1. The table reveals the multitude of different modelling concepts applied using the data derived from the Fracture Zone Project. The choice of the interference tests and tracer tests performed at the Finnsjön site as a test case for the INTRAVAL Project was also motivated by the large data set available from the site.

Table 5–1. Summary of modelling efforts performed using data determined within the Fracture Zone Project including modelling concepts and references.

Modelling concept	Aim	Reference
FRACTURE ZONE PROJECT		
2D finite element porous medium advection–dispersion (SUTRA)	Steady–state flow simulations for planning and design of tracer and interference tests	Andersson & Andersson, 1987
	Transient flow simulations and predictions for planning and design of IT	Nordqvist & Andersson, 1988
	Numeric simulations of IT	Andersson et al., 1989a
	Flow and transport predictions of RCT	Gustafsson & Nordqvist, 1988
	Flow and transport simulations of RCT	Gustafsson et al., 1990
	Flow and transport predictions of DT	Nordqvist, 1989
	Flow and transport simulations of DT	Andersson et al., 1993.
2D anal. element porous medium	Flow predictions of DT	Nordqvist, 1989
1D linear advection–dispersion–sorption	Transport simulations of RCT	Gustafsson & Nordqvist, 1993.
	Transport simulations of DT	Andersson et al., 1993
Stochastic	Analysis of Conductive Fracture Frequency.	Andersson et al., 1988
INTRAVAL		
3D homogeneous porous medium	Flow simulations of IT	Schwartz et al., 1993***
	Flow and transport simulations of RCT	Schwartz & Dewiere, 1993***
3D heterogeneous porous medium using crack tensor theory	Determination of REV from single hole tests, transport simulations of RCT	Kobayashi & Yamashita, 1993***
2D stochastic fracture network advection–matrix diffusion	Transport simulations of tracer test during IT	Yamashita & Kobayashi, 1992*
2D constant aperture fracture advection–dispersion	Simulations of double–peak from KFI11 during RCT	Grinrod & Worth, 1992*
2D varying aperture channels advection–dispersion	Flow and transport predictions of RCT	Hautojärvi & Taivassalo, 1988**
	Flow and transport simulations of RCT and DT	Hautojärvi et al., 1992*
	Transport simulations of tracer test during IT	Hautojärvi, 1993***
2D varying aperture channels advection–dispersion–diffusion	Flow and transport simulations of RCT and DT	Kimura & Munatake, 1992*
2D porous medium advection–dispersion–diffusion	Flow and transport simulations of DT	Kimura & Munakate, 1992*
2D two layer heterogeneous advection–dispersion	Flow and transport simulations of RCT and DT	Hatanaka & Mukai, 1993***
2D stochastic continuum advection–dispersion	Flow and transport simulations of DT and a generic natural gradient tracer test	Shan et al., 1992
2D porous medium multiple flow path advection–dispersion	Flow and transport simulations of RCT Predictive modelling of DT	Goblet, 1990**
2D porous medium advection–dispersion–diffusion	Transport simulations of RCT and DT	Ng & Kota, 1993***
2D parametric/nonparametric stochastic continuum	Transport from conceived repository below Zone 2	Goméz–Hernández & Wen, 1993***
1D linear advection–dispersion	Transport simulations of RCT	Moreno & Neretnieks, 1992*
1D linear advection–dispersion–matrix diffusion	Transport simulations of RCT	Moreno & Neretnieks, 1992*
SKB 91		
3D deterministic continuum (NAMMU)	Flow and transport simulations including influence of Zone 2	Lindbom & Boghammar, 1992
3D stochastic continuum (streamtubes) (HYDRASTAR)	Flow and transport simulations of a potential repository below Zone 2	SKB 91
3D finite volume (PHOENICS)	Influence of Zone 2 and saline water	Ahlbom & Svensson, 1991
3D discrete fracture network (FRACMAN/MAFIC)–	Rock block simulations, validation against transient single–hole tests	Geier et al., 1992
3D distinct element (UDEC)	Rock mass response to glaciation, influence of Zone 2	Rosengren & Stephansson, 1990

IT = Interference Test, RCT = Radially Converging Tracer Test, DT = Dipole Tracer Test
* = In: Tsang & Neuman (editors) (1992), ** = Also in *, *** = Contributions to INTRAVAL Phase II Working Group 2 Summary Report.

5.2 MODELLING WITHIN THE FRACTURE ZONE PROJECT

5.2.1 Modelling Purpose

The flow and transport modelling was carried out as parts of the sequence of field experiments: the hydraulic interference tests, the radially converging tracer test and the dipole tracer test. Figure 5–1 illustrates the general flow of field experiments and related modelling. Thus, there were several separate modelling efforts. The general purpose for all the modelling described here was to predict each field experiment based on all available information and compare the results with the actual outcome of the experiment. As each experiment was completed, new information could be added to the model in order to improve the predictive ability for the prediction of the following experiment. It was emphasized during the whole sequence that groundwater flow should be predicted as well as solute transport.

In addition to the general modelling purpose described above, model simulations were also performed in order to assist in the design of all the different experiments.

Finally, considerable effort was placed on using models to evaluate and interpret the experimental data with respect to injection schedules, observed occurrence of multiple flow paths, etc.

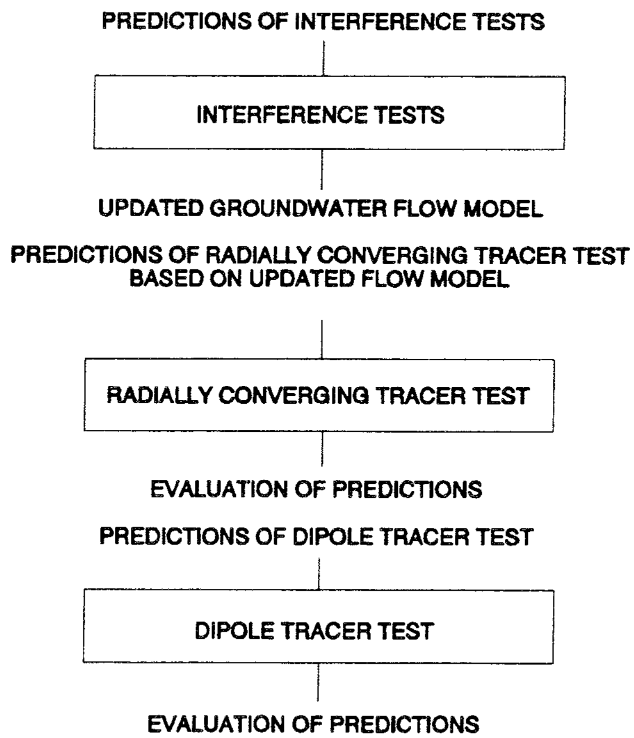


Figure 5–1. General flow of field experiments and related modelling.

Below is a brief description of the modelling concepts and the different steps of the modelling sequence. A thorough description is given in Tsang & Neuman (editors), (1992).

5.2.2 Modelling Concepts

A general approach for the selection of model(s) in this case was that they should be relatively simple, as this should be seen as an initial effort to model the flow and tracer tests at Finnsjön. Thus, for reasons of simplicity, a more or less traditional porous medium approach was taken where the flow domain can be assigned averaged flow and transport properties on the scale of the performed experiments. As the fracture density is high within Zone 2, this assumption should be entirely reasonable. Most of the transport modelling was performed for the upper, 0.5 m thick, highly conductive part of the fracture zone. Some of the flow modelling was also carried out with the entire fracture zone represented as the equivalent to a multi-layered aquifer.

The fracture zone is a fairly well defined horizontal plane, bounded by more or less impermeable boundaries. Thus, a 2-D confined aquifer model was selected, in order to account for effects of hydraulic boundaries on the flow field, especially during the radially converging tracer test.

There was also a desire to use some simple models as a tool for supporting the interpretation of the experimental data, especially with respect to variable injection schemes, different inlet boundary conditions, multiple flow paths, retardation, etc. Therefore, some 1-D transport models were applied. In this case the flow conditions were more or less neglected and only water residence times were considered.

The radially converging flow field was in this case approximated with a linear flow field, which is a reasonable approximation at moderately high Peclet numbers. This approximation was used for reasons of simplicity, since simple analytical solutions exist and parameters can be estimated with a relatively small computational effort. The same assumption was also used in the evaluation of the breakthrough in observation holes during the dipole test. Hence, each observation hole was considered to represent a single flow path. This assumption is obviously not valid for the pumping hole in the dipole field and here breakthrough data were consequently simulated using a 2-D model instead.

In summary, the 1-D modelling can be seen as a natural extension of the analysis of the experiment(s), where the effects of injection stops, multiple flow paths, different tracers, etc, can be checked with a minimum of computational effort. The 2-D model, on the other hand, was used to predict the outcome of each experiment.

5.2.3 Flow Simulations and Predictions of the Interference Tests

Prior to the interference tests, transient flow modelling was carried out in order to predict the interference tests and to assist in the design of the tests /Nordqvist & Andersson, 1988/. The available information was somewhat limited, and consisted mainly of single-hole transmissivity measurements in packed off sections in a number of boreholes. Thus, no averaged properties or boundary conditions were known. In this case a vertical profile with radial symmetry was used, with the fracture zone being represented as a layered aquifer (Figure 5-2). The understanding at this time of the fracture zone was that it consisted of three highly conductive sub-zones, separated by layers of relatively low hydraulic conductivity. As transient drawdown data already existed from measurements during drilling of borehole BFI02 /Ahlbom et al., 1988/, some limited calibration of the model could be carried out. However, only short time series were available in this case and this calibration could at best only yield very approximate values of the hydraulic parameters.

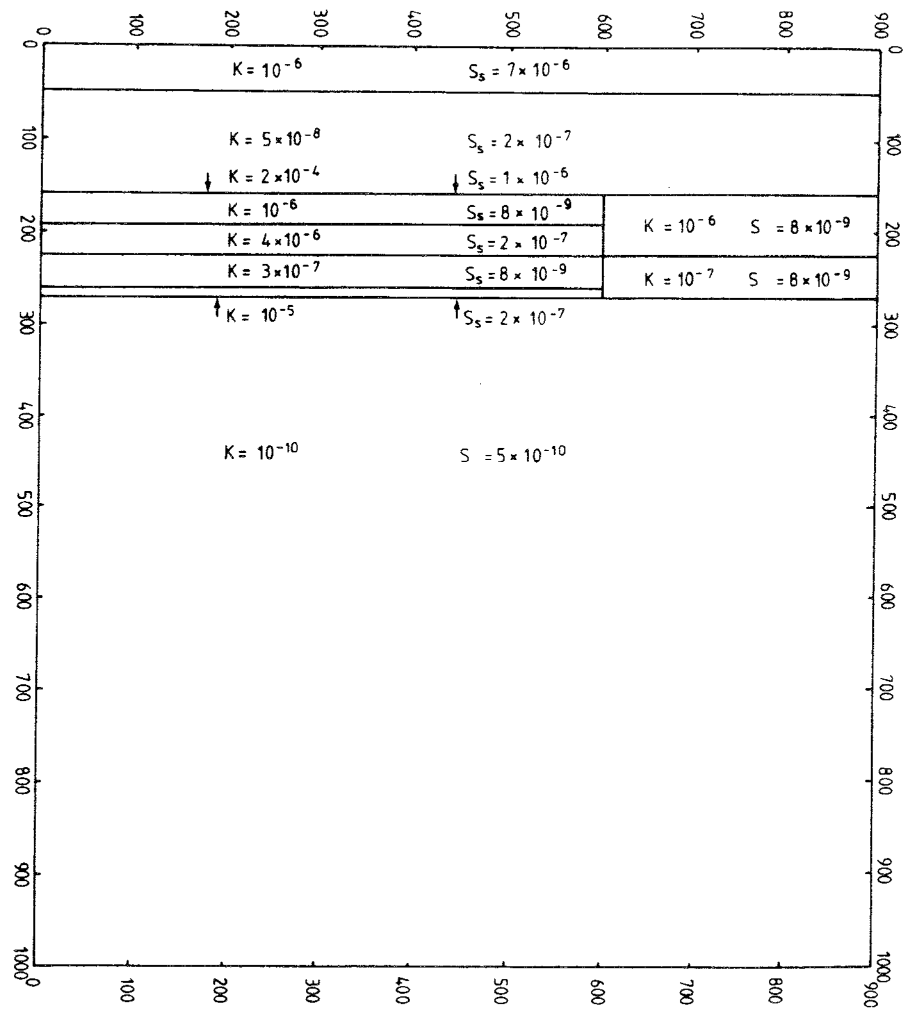


Figure 5-2. Conceptual model and parameter distribution used for the predictive modelling of the interference tests.

The results indicated that the predicted drawdown within Zone 2 was rather uniform in all scenarios (Tests 1, 2, and 3, see Chapter 4.3.3) due to the hydraulic interconnection between the highly conductive layers of Zone 2. Comparisons of predicted versus observed results from the interference tests show that the predictions generally were not very accurate. It is apparent that accurate predictions of this kind were difficult to achieve based on the available information at the time of the prediction. However, by analyzing the discrepancies between predicted and measured results, some valuable information could be gained about the zone.

The model predictions as well as analytical interpretations /Andersson et al., 1989a/ indicated that the previously assumed transmissivity of Zone 2 is somewhat underestimated. Furthermore, the different subzones are not isolated units, but are hydraulically interconnected. This is indicated by the fact that measured drawdowns in different observation sections within the zone for a particular observation borehole in most cases merge to similar values as steady state is approached. The validity of this interpretation is also supported by some parameter sensitivity tests performed during the predictive modelling /Nordqvist & Andersson, 1987/. In one of those tests the layers separating the subzones were assigned a significantly lower hydraulic conductivity than in Figure 5-2. The result was a significant vertical difference in drawdowns between different subzones, which was generally not observed during the interference tests. On the other hand, it should be pointed out that since certain drawdown differences between different sections actually were observed, this may indicate a somewhat lower hydraulic conductivity in the vertical direction. An additional important interpretation was that hydraulic boundaries were not accounted for correctly.

In order to obtain an improved model describing flow in the Brändan area, some additional data needs were recognized. The most important was a better description of the geometrical framework, with respect to the extent of Zone 2 and the nature of its boundaries. Further, values of transmissivity of the zone would have to be refined.

Based on updated interpretations of the geology of the Brändan area and the data collected during the interference test /Andersson et al., 1989a/, a considerably larger flow domain was chosen for the calibrated model, see Figure 5-3. The modelling was performed only in a horizontal plane representing the entire thickness of Zone 2. The zone was modelled as one hydraulic unit with boundary conditions as specified in Figure 5-3. It was not considered relevant to attempt to model any of the subzones separately, since the interference test results indicated that a significant part of the flow originated from vertical flows within Zone 2, when pumping only in one of the subzones. Further, the radially converging tracer test was to be performed by pumping the entire thickness of the zone.

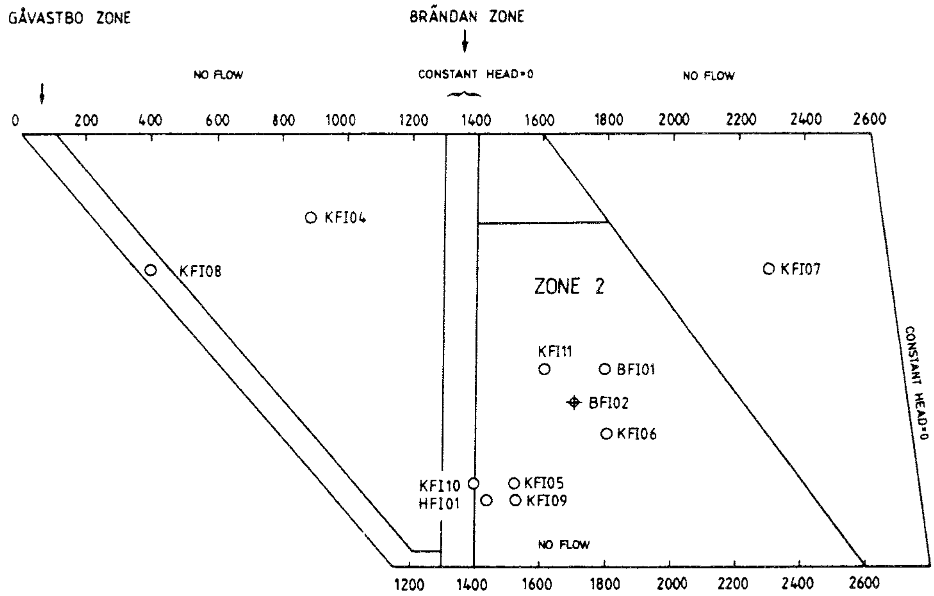


Figure 5–3. Conceptual model and boundary conditions used for the calibration of the interference tests and for predictions of the radially converging tracer test (horizontal plane along the dip of Zone 2).

The general procedure for the calibration was to simulate transient flow, using the assumed geometry of the flow domain, in such a way that an agreement between simulated and measured drawdowns of the primary responses would be achieved.

The "tuning" parameters for the calibration were transmissivity and storage values, and to some extent the boundary conditions. Boundary effects are detected in the transient drawdown curves as deviations from corresponding type curves for infinite aquifers. A combination of transmissivities, storage coefficients and boundaries that would yield a good fit between measured and simulated primary responses, was considered as an indication that these parameters were correctly estimated.

Using the assumed geometry, the parameter distribution yielding the best fit is shown in Figure 5–4. All the separate rock units are here assumed to be homogeneous and isotropic. The separate section at the top of the triangular shape representing Zone 2, was introduced to eliminate undesired effects on flow in the zone of the assigned constant head in the direction of Lake Finnsjön. The hydraulic head distribution near steady state, presented in Figure 5–5, shows a relatively low hydraulic head gradient within the zone due to the high transmissivity, while steep gradients prevail in the rock outside Zone 2.

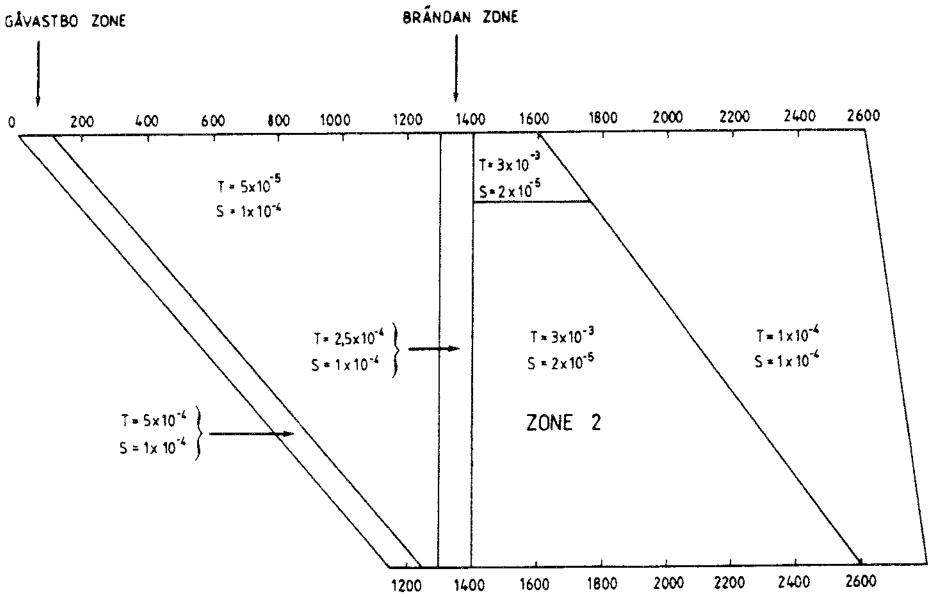


Figure 5–4. Parameter distribution for the calibrated model.

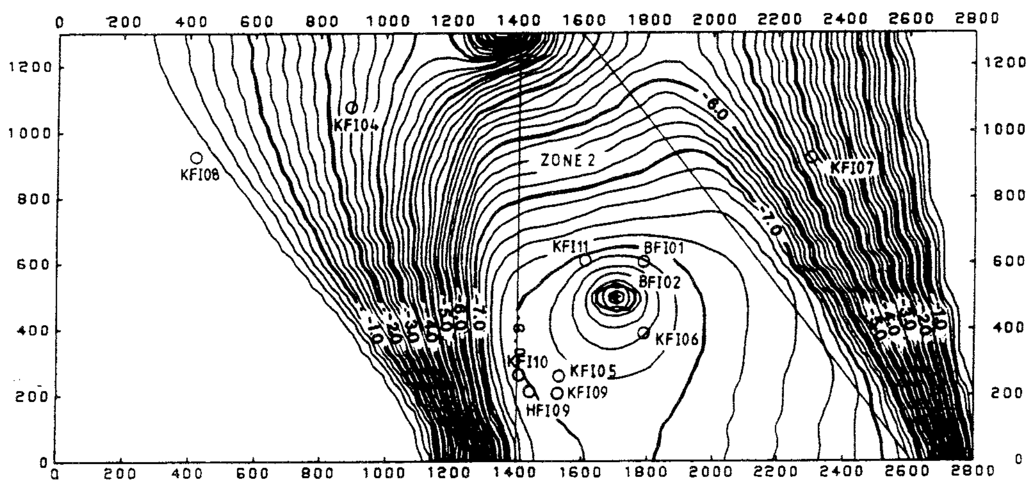


Figure 5–5. Hydraulic head distribution near steady state for the calibrated model.

The transient curves show a relatively good agreement between simulated and observed primary responses. The main exception consists of borehole BFI01, where simulated drawdowns are significantly higher than the observed as steady state is approached. As discussed in Andersson et al.

(1988), measured responses in BFI01 (and to some extent in KFI11) are not consistent with those observed in other boreholes. The behavior of BFI01 is not possible to model using the assumptions of the flow geometry and an isotropic medium. To explain the observed inconsistencies in observed responses in BFI01 one must include properties not accounted for in the present flow model. These may be local heterogeneities close to the borehole. Another possibility would be a general anisotropy within the zone.

Some simulations were carried out in order to study the effects of anisotropic transmissivities. The results indicated that by accounting for anisotropy it may be possible to improve the calibrated model for the boreholes close to the pumped hole, BFI01, KFI06 and KFI11. However, the fits obtained for the observation holes KFI05, KFI09, KFI10 and HFI01 were not entirely satisfactory. The implications of the anisotropy modelling were essentially that more questions were raised than answered. With the assumptions of this particular flow geometry, a general anisotropy in the fracture zone may partly explain the observed inconsistencies for the boreholes close to the pumping hole, but will not improve the calibrated model over the whole flow domain in general. This would suggest that local heterogeneities rather than a general anisotropy cause the inconsistent drawdown behavior in BFI01 (and to some extent KFI11).

5.2.4 Flow and Transport Simulations and Predictions of the Radially Converging Tracer Test

Before the final design of the tracer experiments, a series of 2-D steady-state flow simulations were carried out in order to check the feasibility of performing large scale tracer tests within Zone 2 /Andersson & Andersson, 1987/. Transport distances in the order of a few hundred meters were found to be practical for realistic pumping rates. It was also concluded that the natural groundwater flow was important to consider. Finally, simulations of pumping in three boreholes placed on a line to obtain parallel flow was found to work less satisfactory and was therefore rejected in the final proposal for tracer experiments /Gustafsson et al., 1987/.

The results of the interference tests provided an extensive amount of drawdown data, with which the predictions could be evaluated and the flow model be calibrated and updated as described above. This calibration was made in order to make possible an accurate prediction of the flow conditions during the radially converging test, which was to be performed with a different pumping rate than during the interference tests.

Using the updated model, calibrated using transient pumping test data from eight different boreholes, the steady state flow field for the radially converging test was predicted. Using the flow field (hydraulic head distribution), tracer breakthrough curves were predicted prior to the start of the tracer test. Although information about hydraulic parameters and boundary conditions now was available, very little was known about the transport parameters (flow porosity and dispersivity).

The flow domain for the solute transport predictions in the horizontal plane was chosen as small as possible, enclosing only the boreholes included in the radially converging tracer test, BFI02, BFI01, KFI06, KFI11. A small model domain provides for reducing numerical difficulties and maintaining computational efficiency, by enabling the construction of finer finite element meshes. Separate meshes for the three injection boreholes were used.

The values used for the porosity was estimated from earlier, preliminary tracer tests /Ahlbom et al., 1986/. Dispersivity values were chosen somewhat arbitrarily. Earlier investigations at Finnsjön /Gustafsson & Klockars, 1981/, indicated values of the order of 1 m on a scale of approximately 30 m. However, due to scale effects, dispersivity values were expected to be larger for the radially converging tracer test.

The actual breakthrough curves were obtained by scaling the simulated observations at the point of observation (BFI02) according to some assumptions about the dilution effects in the sampling sections. In this case, a flux-averaging of sample concentration was assumed, with fluxes assigned according to the assumed transmissivities for each layer. It was emphasized that both hydraulic gradients and breakthrough curves should be predicted satisfactorily. Obtaining an accurate breakthrough curve but failing to predict hydraulic head gradients is considered a rather dubious result.

Table 5–2 summarizes the observed head differences for all nine injection intervals as well as the predicted head differences. The measured values were estimated from plotted time series of head differences calculated from manually leveled hydraulic heads.

Table 5–2. Comparison of measured and predicted head differences (units in meters).

Borehole	Section	Measured	Average	Predicted
KFI06				
	Lower	0.62		
	Middle	0.64	0.62	0.42
	Upper	0.59		
KFI11				
	Lower	0.81		
	Middle	0.74	0.77	0.47
	Upper	0.77		
BFI01				
	Lower	1.14		
	Middle	1.25	1.27	0.46
	Upper	1.41		

Table 5–2 again confirms that the groundwater flow model does not explain hydraulic heads in borehole BFI01. For boreholes KFI06 and KFI11 the agreement is better.

A comparison between measured and predicted first arrival times was also made. It may have been more desirable to compare average travel times as the time of 50 % of the steady–state concentration, but those were not well defined in all breakthrough curves. Regarding the predicted first arrival times, the high conductivity zones were considered more accurate with respect to the actual hydraulic conductivities given as input.

The comparison between measured and predicted travel times revealed several interesting features. Firstly, predicted arrival times were significantly underestimated for all sections. Secondly, the assumption that both the upper and lower intervals essentially represent layers with high fluid velocity (during the tracer experiment) was not correct. The only case where this assumption holds was for borehole KFI06. Thirdly, the differences between boreholes in measured first arrival times did not correspond to the prevailing hydraulic gradients. Given that the hydraulic gradients apparently were predicted relatively accurately (except for BFI01), the reason for the discrepancy in travel times is to be found in either the hydraulic conductivities or the flow porosities.

Hydraulic conductivities were measured extensively in the project by single hole injection tests. The conductivities from these agree reasonably well with values estimated from the interference test, and subsequently used in the predictive modelling. Thus, only relatively small errors in predicted travel times can be attributed to wrongly assumed hydraulic conductivities.

The flow porosity for the fracture zone was essentially unknown, and it appears that the prediction error regarding travel times can be explained by this lack of information. The value used for the predictions, 3.0 E–04, was obtained from measurements over 75 m large section /Ahlbom et al., 1986/. However, the flow porosity would be greater in the fracture zone than for the surrounding rockmass. Thus, the value obtained from the 75 m section may significantly underestimate the porosity in the fracture zone. By scaling the porosity valued used in the predictions to a fracture zone with a width of 1.0 m, one obtains a flow porosity of 2.25 E–02.

Using a flow porosity of 2.25 E–02 and with other parameters as before, new breakthrough curves were simulated. These are compared to the observed breakthrough curves in Figure 5–6. In addition to changing the porosity, the concentration boundary condition for the injection well (BFI02) is changed according to measured injection rates of tracers.

In summary, the calibration of the model after the radially converging experiment mainly concerned adjustment of the flow porosity, and some minor adjustment of the hydraulic conductivity. These updated parameters were then used for the prediction of the dipole tracer test.

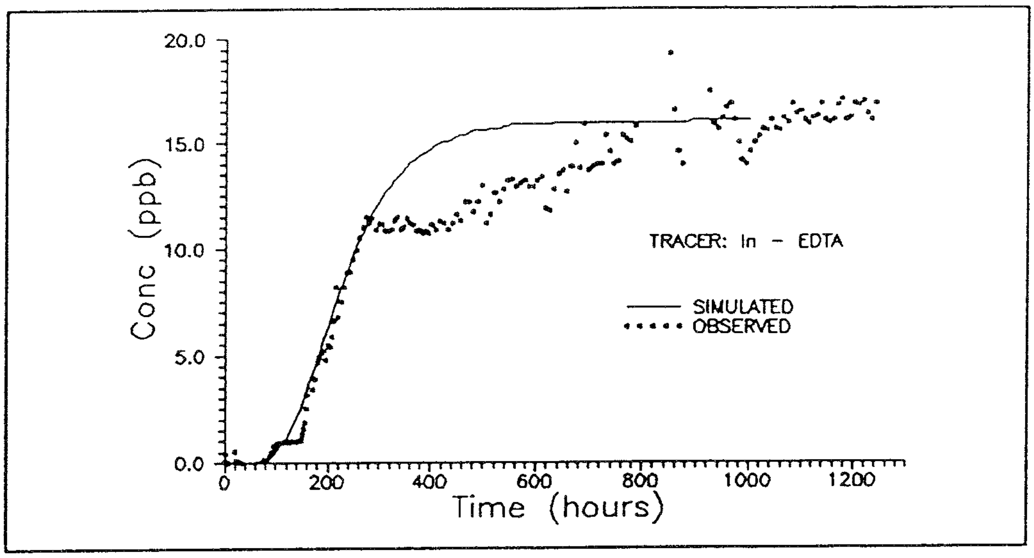


Figure 5–6. Simulated versus observed breakthrough data after adjustment of porosity.

5.2.5 Flow and Transport Simulations and Predictions of the Dipole Tracer Test

An evaluation of the radially converging test yielded transport parameters that could be used for predicting the dipole test. The model geometry for the dipole test was somewhat different than for the previously described tests. In this case pumping (with re-circulation) was performed only in the uppermost, 0.5 m thick layer of the fracture zone. Based on the fact that there would be no net changes in fluid storage in this layer, it was assumed that also this thin layer could be modelled in two dimensions.

Some preliminary flow modelling was carried out in order to investigate the influence of hydraulic boundaries and natural gradients on the flow field /Andersson et al., 1993/. It was found that the assumed hydraulic boundaries were not important, while the natural gradient (measured in a limited number of boreholes) had an influence on the dipole flow field.

The solute transport predictions were all based on the relatively simple flow geometry arrived at during the preliminary calculations of the flow field configuration. Thus, a natural gradient of 1/300 was assumed and no particular boundary conditions were applied. The flow and transport domain includes the injection borehole, BFI01, the pumped borehole, BFI02, as well as boreholes KFI06 and KFI11. Homogeneous and isotropic conditions were assumed. Thus, it was not expected that the groundwater velocity distribution should be correctly simulated across the entire computational domain.

Given the lack of a detailed description of the geometrical features, parameters were estimated so that solute transport between BFI01 and BFI02 was expected to be modelled as accurately as possible. The modelled physical processes were advection/dispersion, radioactive decay and adsorption.

Simulation of sorbing tracers requires characterization of the sorption processes. In this case a linear relationship between sorption density and solute concentration in the fluid was assumed. Literature data are usually expressed as linear relationships. However, since the solute concentrations were expected to vary significantly in magnitude during the dipole tracer test, it may be questionable if a linear relationship is appropriate. As adsorption density on the rock surface increases, it is reasonable to expect that adsorption characteristics will change. However, the simplest possible approach was taken, and linear isotherms were assumed.

The usual way of expressing K_d-values (adsorption equilibrium constants) as sorption per mass solid is inappropriate for flow in fractures. Instead, adsorption should be related to the available surface area of the rock. However, this requires data on available surface for adsorption in the fractures. Lacking such data, a formation factor, f, is used. This concept was adapted by Gustafsson & Klockars (1984), in order to account for the inadequacy of applying adsorption per mass relations rather than adsorption per surface area. Thus, lacking information on surface area available for sorption, an f-value was selected such that a range of retardation factors, R, was simulated. The f-value is in a general way thought to be related to the flow porosity, but was here somewhat arbitrarily set to 0.001. In other words, retardation factors rather than K_d-values were used in the simulations.

Figure 5-7 shows predicted and observed breakthrough curves in borehole BFI02 for a conservative tracer. Average travel time and peak level was predicted relatively well, but it is evident that a fairly large amount of the injected tracer mass was lost. Based on measurements of salinity during the experiment, it is indicated that some of the discharged water originates from below, where the salinity increases sharply. Thus, the dipole field, which is assumed to be two-dimensional, would have a three-dimensional component. A simple mass balance gives a preliminary estimate of the contribution of high-salinity water to the discharged water, indicating that possibly as much as 30 percent of the injected tracer mass would be lost (or delayed) due to this effect. However, it is difficult to interpret the apparently high salinity since this may be a transient effect developed during the initial stages of pumping.As far as predicting the flow field, the observed head difference between the injection hole and the discharge hole was almost identical to the predicted /Andersson et al., 1990/.

The evaluation of the dipole tracer test also involved an analysis of the impact of the magnitude and direction of the natural gradient and if tracer breakthrough in all three observation holes could be explained simply by assigning anisotropy to the zone /Andersson et al., 1993/.
Simultaneous fitting of all three breakthrough curves was made by inverse

modelling technique. The simulations showed that it was not possible to explain the observed breakthrough simply by adjusting the magnitude and direction of the natural gradient. However, by assigning an anisotropy to the upper subzone, all three curves could be reasonably well fitted using one set of parameters. An anisotropy factor (K_{max}/K_{min}) of 8 and a direction very close to the strike direction of Zone 2 was found to give the best fit. This result is interesting as it suggests that the highest transmissivity should be expected along the strike direction of the zone. The result also seems to agree with the geological character of Zone 2, see Figure 3-2. The stepwise extension along the dip direction of the zone may decrease the connectivity along this direction while the zone still may be well connected along the strike direction /Andersson et al., 1993/.

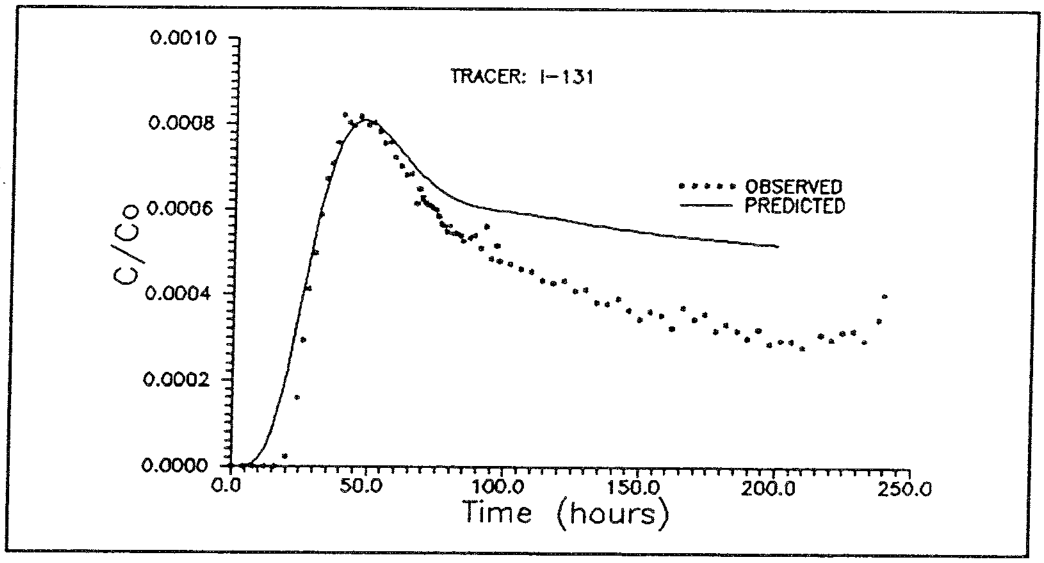


Figure 5-7. Comparison of model predictions and experimental results from borehole BFI02 during the dipole tracer test.

5.2.6 One-Dimensional Transport Modelling

The above described sequence concerns the two-dimensional modelling. In addition, one-dimensional models were used for evaluation of the tracer tests. In this case, very little consideration was given to the flow hydraulics and only water residence times were of interest. These models were used with the slightly different purpose of making possible some interpretations primarily about the transport connectivity between the different injection sections and the sampled borehole. It is emphasized that information from the whole sequence of experiments provided a basis for these interpretations.

The analysis generally assumed steady-state flow, but accounted for variable injection schemes. An important difference, compared to the 2-D modelling, is that mixing in the sampled borehole of tracers travelling through several different major flowpaths is considered. As independent measurements (other than the breakthrough curves) indicated the existence of such multiple-path transport, this approach proved particularly useful.

The general approach was to estimate transport parameters by non-linear regression, using various analytical one-dimensional models as given by Van Genuchten & Alves (1982). The regression method was in this case used as a tool to answer the question: What model and what parameters explain observed data? Thus, it is also an exercise in model discrimination, although only advection-dispersion transport models were considered in this case. The models are described in Gustafsson & Nordqvist (1993).

The fitting was generally made for three parameters, dispersion coefficient, D, mean velocity, v, and proportionality factor, f. The f-parameter is the product of injection concentration, dilution in the sampling section, and a weight representing the contribution from each main flow path. The fitted parameters were transformed into the form of more conventional transport parameters: residence time, t_0, dispersivity, D/v, and Peclet number. The uniqueness of the parameter estimates was assessed by studying the regression statistics of each model run: the correlation coefficients, standard error of the parameters, and the correlation between the parameters /Gustafsson & Nordqvist, 1993/. The classification was made on a scale from 1 to 3 where 1 represents a poor model, 2 represents an acceptable model, and 3 a good model.

An example of a model fit to experimental data is shown in Figure 5-8 for the tracer In-EDTA which was injected as a step input in borehole BFI01, in the uppermost highly conductive layer of Zone 2. From detailed sampling at different levels in the fracture zone during the radially converging test, it was evident that at least two major flow paths were contributing to tracer arrival in the sampled section /Gustafsson et al., 1990/. Similar indications were also found from the interference tests, by analysis of primary and secondary pressure responses /Andersson et al., 1989a/.

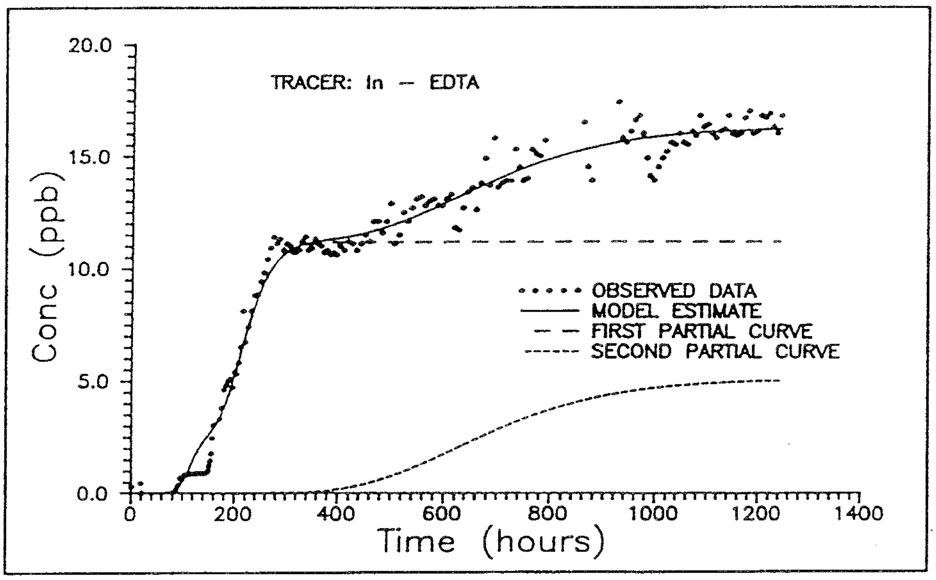


Figure 5-8. Regression estimate for In-EDTA with a two-path model.

It should be noted that whenever two or more flowpaths were considered for an injection in the upper 0.5 m part of the fracture zone, this was interpreted as if most of the transport was taking place in the upper part as spreading in a plane, while the other flowpath(s) may just be "channels" of preferential flow. The understanding of Zone 2 at this stage of the investigations changed somewhat, meaning that the fracture zone did not really consist of separate sub–layers as was thought prior to the interference tests. Only the upper, 0.5 m thick, highly conductive part was considered with certainty to be a well-defined plane, with the possibility of a similar plane at the bottom delimitation of the zone as well. In between, there would be patches of more or less vertical connections within the fracture zone.

Gustafsson & Nordqvist (1993) also demonstrate the importance of accounting for variations in the tracer injection. By considering pump stops or other flow variations, breakthrough curves with very irregular shapes could be explained. An example is shown in Figure 5–9 for ReO_4 which was injected as a step injection in borehole KFI06 in the lower part of the fracture zone. In this case the tracer mass injection varied significantly with time, and at least two main flow paths were observed. The bulk of the tracer arrived in the lower part of the fracture zone, while a smaller part arrived in the upper part. Regression with a two path model, accounting for the variable mass injection, is presented in Figure 5–9. Data is very well explained by the model up to around 2000 hours. The remaining tailing beyond this point is not explained. Regression runs using three flow paths did not improve the model fits as desired if advection/dispersion was the only process governing tracer transport. Other processes, such as matrix diffusion and/or transient solute storage may explain the difference between model fit and experimentally obtained data.

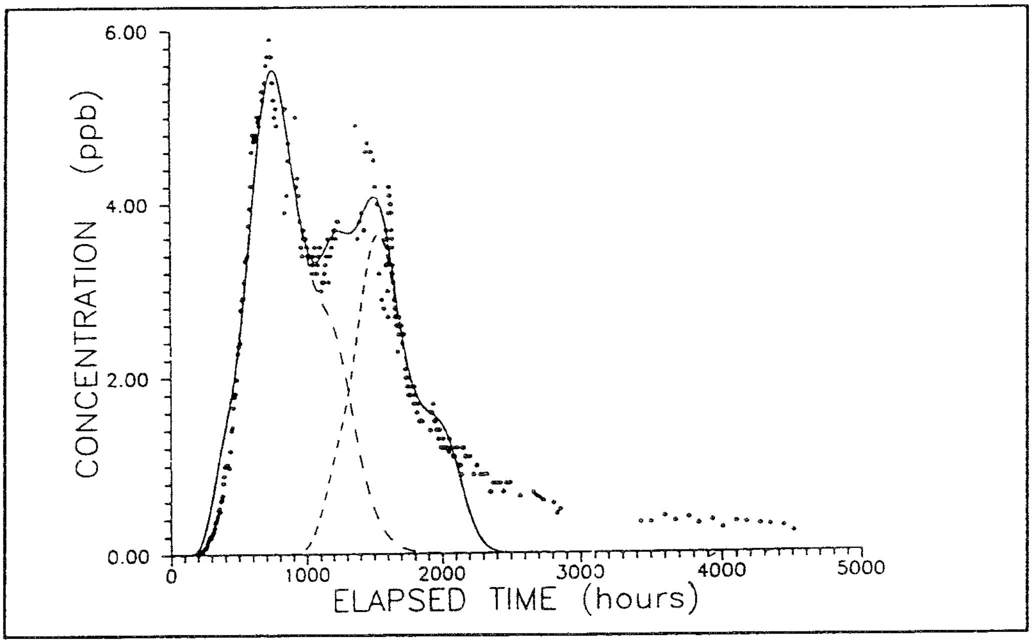


Figure 5–9. Regression estimate for ReO_4^- assuming two major flow paths and applying a variable injection scheme.

The evaluation of the radially converging test also involved determination of transport parameters using analytical methods. Gustafsson & Nordqvist (1993) made estimates of the number of fractures contributing to the flow in Zone 2 based on the ratio of cubic law aperture to mass balance aperture according to Silliman (1989). They found that in the upper part of the zone only 1–7 fractures contributed to the groundwater flow during the radially converging test, while in the middle and lower parts, the number of contributing fractures is markedly higher (10–100). By using this fracture density Gustafsson and Nordqvist (1993) also calculated the **flow wetted surface area per volume of rock.** They found values of 1–56 m^2/m^3 for the upper subzone depending on direction, with the lowest numbers (1–8 m^2/m^3) for the flow path between KFI11 and BFI02. The values were calculated assuming that the entire area of the fractures is available for transport which probably is not correct as preferential flow paths is likely to exist.

Gustafsson & Nordqvist (1993) also estimated the **flow wetted surface area per volume of water** using the single fracture apertures determined from tracer breakthrough data. They calculated values ranging between 1180 and 3850 m^2/m^3 for the upper subzone. This is similar values as determined for a minor fracture zone at the Stripa mine, 1266 m^2/m^3 /Andersson et al., 1989b/.

Similar regression runs were performed using the breakthrough data from the dipole tracer test /Andersson et al., 1993/. In this case only data from the two observation holes KFI06 and KFI11, representing individual flow paths, were used. A summary of the modelling runs are presented in Table 5–2. A total of 34 simulations were performed including 15 different tracers. The simulations also included parameter estimation using 2 or 3 breakthrough curves simultaneously for determination of retardation coefficients.

Most of the model simulations presented in Table 5–2 are judged to be acceptable or good, based on the concept described above, with only one main flow path between BFI01 and KFI11. The variation in residence times and dispersivities is small except for the weakly sorbing tracers La–140, Lu–177 and Rhodamine WT. These tracers are markedly delayed.

The breakthrough in KFI06 is markedly delayed compared to KFI11. The long residence times only enabled detection of the rising part of the breakthrough curves. These model simulations are therefore more ambiguous and consequently classified as being poor with the exception of Rhodamine WT which was monitored during a longer time interval than the other tracers.

Table 5-2. Summary of 1D-model simulations of the dipole tracer test.

Transport path	Tracer	Run	t_0 (h)	D/v (m)	f	Class*
BFI01-KFI11 distance: 165 m	Br-82	1	22.8	11.9	1.07	2
		6	23.2	7.4	0.99	3
	Re-186	2	24.1	7.8	0.83	2
		6	22.8	7.6	0.87	3
	I-131	3	22.9	6.8	1.15	3
		6	23.2	8.2	0.92	3
		3+6	22.6	6.9	1.01	3
	Na-24	6	22.6	5.5	0.50	2
	La-140	7	33.0	17.3	0.93	2
	Lu-177	7	44.0	25.7	0.91	2
	Cr-51	7	24.6	10.0	0.86	3
	In-111	7	24.7	10.2	1.02	2
	Tb-160	7	22.2	9.2	0.44	2
	Yb-169	7	22.8	7.7	1.11	3
	Co-58	8	22.9	7.3	0.62	3
	RdWT	A	30.5	20.8	1.26	1
		E	35.7	23.6	0.93	2
	In-EDTA	C	27.4	14.6	0.25	2
	Gd-DTPA	D	22.7	7.4	0.38	3
	Tm-EDTA	D	23.4	9.9	0.42	3
BFI01-KFI06 distance: 223 m	I-131	3+6	1200	78.1	4.04	1
	Cr-51	7	513	23.4	0.41	1
	Yb-169	7	625	48.2	0.77	1
	Co-58	8	484	26.4	0.28	1
	RdWT	A	622	21.4	0.27	2
KFI11-BFI02 distance: 157 m	I-131	9+10	34.2	8.4	0.03	2

* Classification of model: 1=poor, 2=acceptable, 3=good

5.3 MODELLING WITHIN THE INTRAVAL PROJECT

5.3.1 General

The tracer tests and interference tests performed within the Fracture Zone Project were also selected as a test case in both Phase 1 and Phase 2 of the on-going international INTRAVAL Project. So far, Phase 1 of the project has been finished and reported /Tsang & Neuman (editors), 1992/ while the second phase, aiming at concentrating on a few test cases, is still in progress.

Totally seven different modelling teams analyzed one, two, or all three tests during Phase 1 of the project. Notable is that all seven teams used different modelling concepts, see Table 5-1. Included in the seven teams are also the modelling efforts performed as a part of the Fracture Zone Project, see Chapter 5.1.1. Presently, in Phase 2 of INTRAVAL, the Finnsjön experiments are modelled by nine teams. Their modelling concepts are also summarized in Table 5-1.

One unique feature of the series of tests, compared to the other test cases within INTRAVAL, was that the radially converging and dipole tracer tests had not been started at the beginning of the INTRAVAL Project and it was therefore possible to calibrate the models using data from previous tests and predict the outcome of the tracer tests. This was also done by three of the modelling teams /Hautojärvi & Taivassalo ,1988/, /Moreno & Neretnieks, 1989/, /Goblet, 1990/.

The modelling within the INTRAVAL Project will not be discussed in detail but a brief summary of the results and conclusions from some of the modelling exercises will be given below.

5.3.2 Flow Properties

Only one of the modelling efforts included an evaluation and simulation of the flow field within Zone 2 using data from the interference tests /Schwartz et al., 1992/. All other modelling efforts used input data on transmissivities directly from Andersson et al. (1989a) neglecting to evaluate the interference tests and neglecting effects of boundaries. Schwartz et al. (1992) made a thorough evaluation of the interference tests using both analytical solutions and a 3D finite difference model. Their conclusion based on the analytical solutions was that effects of boundaries could be clearly identified and needed to be included. They also concluded that the fracture system was complex and that it was difficult to link the boundaries determined from their interpretation to actual fracture zone geometry. The transmissivity values determined from the analytical solutions were very similar (within a factor 2) to the values determined by Andersson et al. (1989a).

Many of the modelling teams have recognized the heterogeneous nature of flow but have neglected to use available data from interference tests and from the detailed sampling during the radially converging test. Several modelling teams explain the heterogeneous flow by introducing channels having different flow and transport properties, e.g. Hautojärvi et al. (1992), see Figure 5-10. They consider the differences in flow and transport properties to be an effect of whether the borehole hits the channel or not. If the connection is poor, flow and transport occur through smaller, less transmissive channels connected to the large channels at some distance away from the borehole. They also consider the fact that the measured flow rates through the boreholes are much larger than would be expected from a pure geometrical point of view. This may be an effect of the borehole itself interconnecting several water conducting fractures having slightly different head and thereby increasing the flow through the borehole.

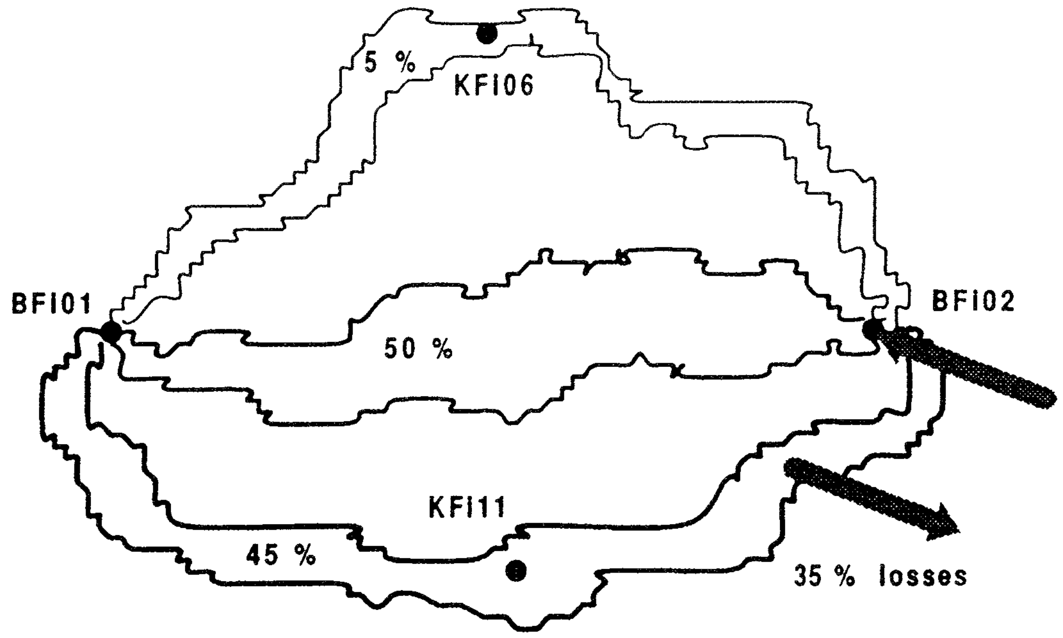


Figure 5–10. Conceptual model for the dipole experiment with three flow routes having different relative flow rates. The flow routes are modelled to go via or very near the observation boreholes /Hautojärvi et al., 1992/.

A similar approach was taken by Kimura & Munatake (1992) using a variable aperture channelling model with a log–normally distributed aperture. They also used a porous medium model and concluded that both models were able to reproduce the flow data but that only the variable aperture model could reproduce the breakthrough in the observation boreholes during the dipole test.

In the second phase of INTRAVAL there is a clear trend towards stochastic modelling. The reason for this is the limited amount of "real" data available in combination with the heterogeneous nature of fractured rock. Shan et al. (1992) applied a stochastic continuum approach to the dipole tracer test. The specific objectives of the approach was to determine "whether the stochastic continuum approach can be successfully used to validate transport of tracer in fractured crystalline rock". The idea was to simulate the dipole test and to calibrate the model in two different ways: by selection of the best fit parameters and by selection of the best fit realizations. Finally, a natural gradient tracer test was simulated in order to explore whether a stochastic continuum model calibrated on a local scale can be validated on a larger scale. The results show that calibration in a local scale is insufficient for validating the model on a large scale. There is also a clear need of measurement data on relevant scales to reduce the uncertainty and subjectivity in the calibration and validation of stochastic continuum models.

Another stochastic approach to deal with the heterogeneity of Zone 2 was employed by Yamashita & Kobayashi (1992) using a 2D fracture network model. They concluded that the flow rates determined were lower than the measured ones and that the reason for this may be that their generated fracture networks were not adequate to represent Zone 2.

5.3.3 Transport Properties

Because of the variety of modelling concepts applied to the transport of solutes in Zone 2, it is difficult to compare different models as they determine different parameters in different ways. However, there are a few parameters, like dispersivity and flow porosity, that may be compared. In Table 5-3 is presented an attempt to compare the dispersivities determined by the different modelling teams.

Table 5-3. Longitudinal dispersivities determined from the radially converging tracer test in the upper part of Zone 2.

Modelling team	Concept	Dispersivity (m) BFI01	KFI06	KFI11	
Gustafsson & Nordqvist (1993)	1D, one path	84	24	40	
	1D, two paths	6	11	4	(path 1)
		8	57	11	(path 2)
Moreno & Neretnieks (1992)	1D, one path	41	32	111	
	+ matrix diffusion	9	-	46	
Goblet (1990)	2D, one path	-	25	10	
	2D, two paths	10			(path 1)
		10			(path 2)

Table 5-3 clearly illustrates that variations are relatively large for different concepts. However, it is not possible to state that one value is more correct than another just by studying the model fitting to the experimental data. Instead, the validity of applying a specific concept should be discussed, e.g. if there are other, independent, data that may confirm a multiple pathway model or a model including matrix diffusion. Such data was available from the detailed sampling procedure, the interference tests, and from laboratory data, but only a few of the modelling groups utilized this independent information.

Flow porosities were generally found to be high, ranging between 0.2-2.5 %, with a maximum in the direction of BFI01. In addition, a number of other transport parameters or lumped parameters like fracture aperture, fracture transmissivity, channel flow rates, channel width, diffusivity, effective thickness etc. were determined, but these are difficult to compare to each other due to the different modelling concepts.

It is obvious from the description of the different modelling efforts and their respective conclusions that it is difficult to draw any definite conclusions regarding transport properties of Zone 2. However, a few general conclusions can be drawn:

- Flow is generally considered to be governed by advection–dispersion. Only one team considered dispersion to be neglible. Instead, matrix diffusion was regarded to be dominant /Yamashita & Kobayashi, 1992/. Moreno & Neretnieks (1992) suggest that a combination of the two processes may be correct although it is difficult, or even impossible, to separate the two processes. Hautojärvi et al. (1992) suggest that matrix diffusion cannot be identified in these short term experiments and therefore may be neglected.

- Zone 2 is a complicated structure where transport occurs in several interconnected pathways. Modelling concepts varying from porous medium to distinct channels all seem to reproduce the tracer data fairly well.

- It is important to carefully consider the source term. Variations caused by pump stops etc. may help to discriminate between modelling concepts.

- The tracer tests performed within the Fracture Zone Project cannot be used to validate transport models. More independent information about geometry and heterogeneity of the system is needed. The modelling groups generally neglected to use all data available, e.g. data from interference tests and laboratory data of diffusivity and porosity.

- Tracer tests performed under very different flow conditions and geometries are needed, e.g. natural gradient tests.

One objective of the INTRAVAL Project was to bring modelers and experimentalists together for a better interaction and mutual understanding. It also resulted in suggestions for future experiments and comments about the Finnsjön tracer tests. These comments, given in Tsang & Neuman (editors) (1992), reflect the main problem for the experimentalists designing a tracer test, namely to design tracer tests and investigation programs that satisfy data needs for many different modelling concepts.

5.4 MODELLING WITHIN THE SKB 91 STUDY RELATED TO ZONE 2

Due to the extensive amount of data collected at Finnsjön, the site was chosen as an example for the SKB 91 study, aiming at examining how the long–term safety in a final repository is affected by the geological characteristics of the repository site. This Chapter deals with some of the items related to Zone 2:

- the impact of density gradients on groundwater flow
- the importance of Zone 2 for rock stability during glaciation
- the importance of the presence of Zone 2 for flow
- to what extent information regarding Zone 2 was used in SKB 91

5.4.1 Impact of Density Gradients on Groundwater Flow

During the investigations at Finnsjön it has become clear that Zone 2 plays an important role in relation to the presence of saline water below the zone. In other parts of the area, the depths to the saline water vary considerably. Ahlbom (1991) presents a conceptual model where it is assumed that saline sea water has been trapped beneath the flat farmland to the east of the Finnsjön site. By assuming that the farmland could be viewed as a conceptualized sea, the interface between saline and non-saline waters occurs as an enhanced mirror to the variations in the groundwater table. The model results for a profile across the Brändan area presented in Figure 5-11 are able to explain the distribution of saline water as it is currently known. The figure also clearly show the influence of Zone 2 where the position of the saline/non-saline interface is governed by the hydraulic head in Zone 2. It should be noted that the model is built on the assumption that Zones 14 and 3 are in hydraulic contact with both Zone 2 and the atmosphere. This model also explains why no saline water is found south of Zone 1 (where Zone 2 is lacking) in spite of boreholes down to 600 m depth.

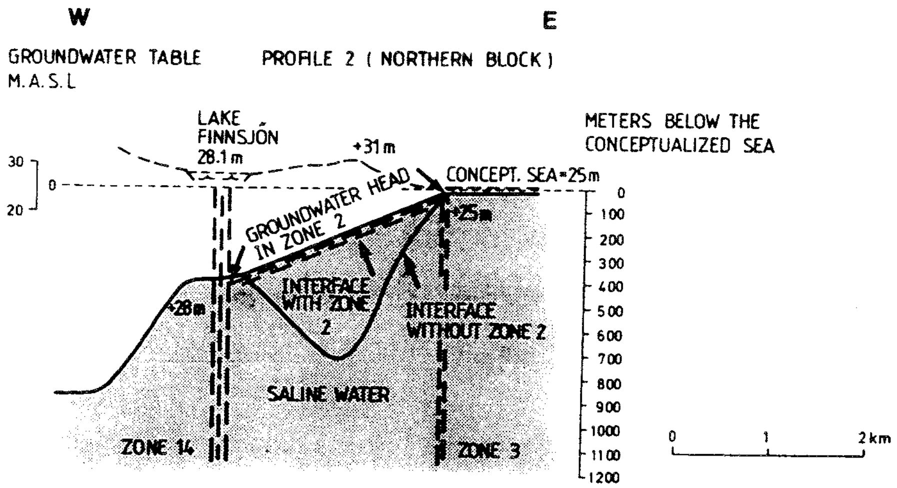


Figure 5-11. Schematic cross-section (West-East) with estimated depths to the non-saline/saline interface at the Finnsjön site and its surroundings /Ahlbom, 1991/.

Another conceptual model explaining the trapping of saline water below Zone 2 is suggested in Svensson (1991a, b). Due to the high transmissivity, Zone 2 will have a more or less constant and low pressure compared to the surrounding rock. Salt water will be driven towards the zone from below but will be trapped due to the high transmissivity. Thus, the clay cover east of the site is not needed to explain the trapping of saline water, as assumed by Ahlbom (1991).

Both models are based on assumptions which have not been tested and on some rough estimates and it is not possible to verify the models with the data presently available. However, based on field observations, e.g. point dilution measurements and water chemistry in the deeper parts of Zone 2, where almost stagnant conditions have been found, the model described by

Ahlbom (1991) is partly verified.

5.4.2 Importance of Zone 2 for Rock Mass Response to Glaciation

The effects of a glaciation on rock stresses at the Finnsjön site have been investigated by means of computer simulations using a 2-dimensional distinct element model (UDEC) /Rosengren & Stephansson, 1990/. The simulations involved an ice-age scenario with a 3 km thick ice load. Totally 6 simulations were made using different boundary conditions. Two slightly different geometries of Zone 2 were also simulated but the results revealed only minor changes in stresses, displacements and failure of fracture zones.

The results of the simulations display that the model was sensitive to the boundary conditions applied. A boundary condition with specified boundary elements for the bottom and sides gave higher horizontal stresses than moving boundaries (roller boundaries).

The modelling also demonstrated some interesting results with respect to Zone 2:

- Most of the displacements of fracture zones are taken up by Zone 2.

- Major stress discontinuities exist in the vicinity of fracture zones and these should be accounted for in siting of a repository.

- Future displacements due to glaciation and deglaciation are most likely to occur in existing fracture zones.

- Simulation of isostatic movement showed large displacements and failure of fracture zones especially during melting. Zone 2 and some steeply dipping zones fail.

- Based on the large stress disturbances and failures, a protection zone of 100 m from the outer boundary of the zone to the repository, is suggested.

Although the simulations gave some interesting results, it should be noted that there are large uncertainties regarding boundary conditions and selected input parameters. A sensitivity analysis for the most critical parameters will enhance the understanding of rock mass response to glaciation /Rosengren & Stephansson, 1990/.

5.4.3 Importance of Major Subhorizontal Zones for Flow

Groundwater flow modelling in a regional flow domain using a deterministic continuum model (NAMMU) was performed within SKB 91 with the main objective to create a reference case for the far field flow analysis /Lindbom & Boghammar, 1992/. The model is based on the results from the Fracture Zone Project compiled in Andersson et al. (1991). The modelling involved a number of sensitivity studies, e.g. effects of the conductivity contrast between fracture zones and rock mass. The modelling also involved some sensitivity analyses with regard to the presence of major subhorizontal zones. Three variations were considered. In the first case, Zone 2 was neglected. In the next case, Zone 2 and a generic subhorizontal zone, having the same properties as Zone 2 and located 600 m below, were modelled. In the third case only the generic zone was considered.

The sensitivity analysis showed that the presence of high conductive fracture zones had a relatively strong influence on the results, particularly the situation with such a zone located below a repository without the presence of a similar zone above. Travel times from the repository level to the ground surface were reduced with 85% compared to the reference case. However, it should be noted that the modelling was performed assuming non-saline water in the whole modelling domain. As shown by Ahlbom & Svensson (1991), c.f. Chapter 5.4.1, the presence of saline water may have significant effects on fluxes.

Similar variation analyses were also performed within SKB-91 using a stochastic continuum approach (HYDRASTAR) /SKB, 1992/. The results show that if the diverting and gradient-equalizing effect of Zone 2 is removed, the flows from a repository below the zone increase slightly, see Figure 5-12. In the case of a deeper located low angle zone parallel to Zone 2, the results show a substantial shift towards shorter travel times, i.e. similar results as obtained by Lindbom & Boghammar (1992) (Figure 5-12). Also these simulations were made without considering effects of saline water below the upper boundary of Zone 2.

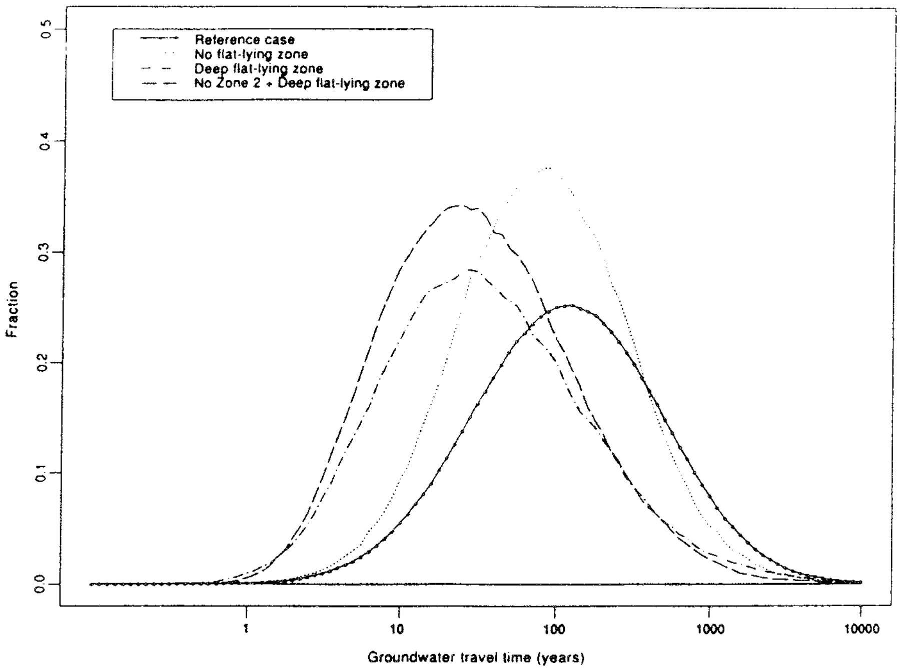


Figure 5-12. Floating histogram of travel times for water from the repository to the surface for a number of variations /SKB, 1992/.

Based on the results from these sensitivity analyses it seems clear that Zone 2 has a large local effect on flow, but as the models cover a much larger area it is difficult to notice effects on the regional flow. The regional flow in the NAMMU and HYDRASTAR models /SKB, 1992/ is to a large extent driven by the topography and the regional zones, where connectivity and transmissivity are virtually unknown. Instead, the modelling may be seen as an example of how the flow distribution and groundwater fluxes would look like under given conditions. There are several uncertainties, e.g. the connectivity of the fracture zones and the regional gradient, which may significantly affect the flow distribution. Other modelling efforts, e.g. Ahlbom & Svensson (1991), have indicated that the presence of saline water beneath the upper boundary of Zone 2 has a great impact on flow and gradients, c.f. Section 5.4.1. There are also large uncertainties in the hydraulic properties assigned to the rock mass and fracture zones other than Zone 2 due to the limited number of boreholes.

6 EXPERIENCES FROM THE FRACTURE ZONE PROJECT

6.1 RELEVANCE AND RELIABILITY OF METHODS FOR IDENTIFICATION AND CHARACTERIZATION OF FRACTURE ZONES

6.1.1 General

The Fracture Zone Project has involved a large number of different methods during different stages of the project. However, in an "ordinary" site characterization the number of boreholes and investigation methods used for characterization of a specific fracture zone are likely to be much more limited due to costs and the fact that too many boreholes may affect repository safety. Therefore, it is important to select the methods best suited to characterize the rock and fracture zones.

The project has demonstrated that these kind of investigations need to be operated in an iterative way, where geological, geophysical, hydrogeological, and hydrochemical investigations have to be applied in different scales and in different stages of the project. The Fracture Zone Project also demonstrated that reinterpretation of old data may be very useful after collecting new data. This may sometimes even be a better method than trying to collect more new data. Examples of this in the Fracture Zone Project is core data and geophysical data that were reinterpreted after the hydraulic tests.

Below is a summary of the experiences gained about methods and applicability of methods for characterization of crystalline bedrock and, in particular, fracture zones.

6.1.2 Geological Methods

Geological interpretations of fracture zones are subjective to their nature. Therefore, it is important that the geological interpretations are integrated with geophysical and geohydraulical investigations in an iterative way. Within this project a close collaboration of experts from different fields have shown to improve the understanding of both geology and hydrology of the area.

One of the main difficulties recognized in this project is the identification of low angle structures from ground surface geological and geophysical measurements. The reason for this is their diffuse outcrop over a large area which often does not create a marked depression in the landscape. Zone 2 is a good example of this, where the possible outcropping area is covered by clay and therefore not visible and possible to locate exactly. The zone may also end towards another zone and thus, not outcrop at all. Ground geophysical methods were not fully developed at the time of this investigation, but reprocessing of the reflection seismic data has indicated that this method may be applied in the future for identification of low angle structures. The fact that Zone 2 was not identified in the earlier performed site investigations at Finnsjön is an excellent example of the difficulty to identify low angle structures, even extremely large ones.

Lineament interpretation from satellite/airphoto images, topographical maps and air-borne geophysics is likely to be the only method for identification of some of the regional structures that constitute the boundaries for an investigated area. Tirén (1986) stresses the fact that lineament interpretation should be performed in different scales, as large scales enhance large features while small scales suppress them.

The mapping of outcrop boundaries proved to be helpful in identifying large fractures/fracture zones, while mapping of fractures within the outcrops themselves, where fracture zones generally not intersect, is more helpful for determining fracture statistics.

The relatively low degree of fracturing within most parts of Zone 2 has demonstrated the difficulty in identification of a fracture zone based on fracture frequency alone. Tirén (1986) states that "the identification of fracture zones within the rock mass should be a question of defining what is anomalous fracturing and what is normal fluctuation of the frequency of fracturing and what limit should be assessed to define a fracture zone".

In Table 6-1 a summary of the most important geological methods for identification and characterization of fracture zones, used within this project, is presented together with conclusions from this project regarding their applicability for fracture zone characterization.

Table 6–1. Geological methods used within the Fracture Zone Project. Summary of aims and comments regarding applicability (fz=fracture zone).

Method	Aim	Comments regarding applicability
Lineament interpretation	Identification of geological structures	Necessary for identification and understanding of structural geology. Identification of low angle structures difficult. Should be made in different scales. Decreases the risk of finding "unexpected" structures later.
Outcrop mapping of fractures	Location of fz (outcrop boundaries). Statistical characterization of fracture population.	Mapping of outcrop boundaries found to be successful in defining configuration of fz. Outcrops represent the more resistant part of the rock and may not be representative of fz. Mapping should be performed across fz.
Drilling	Identification and characterization of fz.	Difficult to identify "unexpected" structures from drilling alone. Fz identification possible in percussion boreholes by monitoring of penetration rate, water yield and collection of drill cuts.
Drill core mapping	Characterization of fz.	Oriented fracture data are preferred. Important to recover as much of the core as possible in crushed parts of the rock. Careful core mapping and correlation analysis can be used to identify and separate fz occurring in the same borehole as well as for correlation between boreholes. Sealed fractures and other signs of tectonically disturbed bedrock is as important to map as "open" fractures.
Analyses of drill cores	Identification of fracture minerals. Support to geophysical measurements.	Reactivated fractures are also the most potential ones to be reactivated in the future.
Collection and mapping of drill cuttings	Identification and characterization of fz.	Fz can be identified. Difficult to compare different zones as grain size and sorting grade also is a function of depth. Sampling at every meter is recommended.

6.1.3 Geophysical Methods

The geophysical investigations performed within this project have been performed for two main reasons: i) to support the geological interpretations of the structural framework of fracture zones, and ii) to test the applicability of both old and new methods for identification and characterization of fracture zones, in particular Zone 2.

A general conclusion from these measurements, using a variety of methods (see Section 2.1.3), is that low angle fracture zones are difficult to identify from ground geophysical measurements. The only direct method that potentially may detect such zones is the reflection seismics. However, the method still needs to be developed, in particular the processing procedures, c.f. Section 4.2.1.

This project has also involved some new geophysical methods, the borehole radar and the tubewave method. The borehole radar was shown to add substantial information regarding the location of fractures and fracture zones. However, some difficulties associated with the method was also recognized: the loss of radar wave penetration due to high porosity in combination with high salinity within Zone 2, and that the method cannot distinguish between water conducting fractures and other features (dikes etc.). Thus, the use of complementary data such as core logs and hydraulic tests are essential. The tubewave method was also found to be able to identify water conducting structures, although only tested in one borehole.

In Table 6–2 a summary of the most important geophysical methods for identification and characterization of fracture zones, used within this project, is presented together with conclusions from this project regarding their applicability for fracture zone characterization.

In summary, the geophysical investigations performed within the Fracture Zone Project have shown to be a good complement to the geological and hydraulical interpretation of the Brändan area. There is still room for improvements of the methods, in particular surface methods for identifying low angle structures. Also, a closer integration with geological and hydrological investigations is recommended.

Table 6-2. Geophysical methods used within the Fracture Zone Project. Summary of aims and comments regarding applicability (fz=fracture zone).

Method	Aim	Comments regarding applicability
SURFACE METHODS		
Slingram and VLF	Identification of fz. Verification of geological interpretation.	Good correspondence with geological interpretation of Brändan. Dip of fz may be determined. Penetration depth limited. Fz need to be relatively steeply dipping.
Reflection Seismics	Identification of fz.	Processing techniques not fully developed. Method has potential of detecting low angle fz.
BOREHOLE METHODS		
Borehole Deviation	Determination of location and orientation of borehole.	Important for definition of fz geometry.
Caliper	Determination of borehole diameter.	Needed for determination of borehole volumes in connection with other geophysical logs and point dilution measurements. Fz often causes increased diameter resulting from rock fall-out.
Natural Gamma	Determination of mineralogical and lithological changes in the bedrock.	Correlation with dikes, etc., good. Inflow of radon charged water may be detected.
Single Point Resistance and Resistivity	Detection of fz and conducting minerals.	Both methods show almost identical patterns. Method proved to be very useful for identification and extension of Zone 2. Distinct anomalies correlated very well with water conducting parts of Zone 2.
Fluid Resistivity (Salinity) and Temperature	Indication of groundwater flow. Identification of saline groundwaters.	Good for identification of upper flowing part of Zone 2.
Sonic Velocity	Identification of fractures and fz. Determination of porosity.	Anomalies correspond well with water conducting parts of Zone 2 (only one borehole tested).
Tubewave	Identification of water conducting fractures.	Very good correlation with later performed hydraulic tests (only one borehole tested). Rough estimates of fracture transmissivity may be obtained.
Borehole Radar	Identification, extension, and orientation of structures.	Valuable tool for identification and orientation of fz. Structures not penetrating the borehole can be detected. Loss of radar wave penetration in Zone 2 due to high salinity in combination with high porosity. Cross-hole measurements and directional antenna further increases the applicability.

6.1.4 Geohydrological Methods

The geohydrological characterization of Zone 2 has involved many new methods and concepts. Many lessons have been learned about the methods and many of the methods first applied in the Fracture Zone Project were later also used in the preinvestigation phase at Äspö Hard Rock Laboratory.

Piezometric measurements were, for the first time, used systematically to monitor head changes in sectionized boreholes. The measurements were shown to add much information regarding hydraulic characteristics and connectivity of the fracture zones. Disturbing events, such as drilling and planned events, such as interference tests, could be monitored and evaluated. The measurements also revealed some problems such as the compensation for the salinity of the borehole water and some instrumental problems related to the construction of the equipment, c.f Section 4.3.1.

The hydraulic test programme also involved several new tests and evaluation of old test methodologies such as:

- comparison between different equipments
- tests in different scales, from 20 m down to 0.11 m intervals
- effects of gas–lift pumping on hydraulic parameters
- interference tests using gas–lift pumping
- interference tests in sectionized boreholes
- combination of interference tests and tracer tests

These tests have provided a large input for the future site characterization programme. Advantages/disadvantages with different equipments have been investigated, problems with large amounts of drilling debris injected into the surrounding bedrock during drilling have been enlightened.

The benefits of performing interference tests using multiple–well multiple–section monitoring of pressure responses have been demonstrated, and the advantages of using tracers in combination with interference tests have been shown.

A summary of the methods used for hydraulic characterization within this project is presented in Table 6–3 together with conclusions from this project regarding their applicability for fracture zone characterization.

Table 6–3 Hydraulical methods used within the Fracture Zone Project. Summary of aims and comments regarding applicability (fz=fracture zone).

Method	Aim	Comments regarding applicability
Piezometric measurements	Determination of natural head distribution	Small head differences difficult to measure due to salinity differences. Correction for salinity necessary. The same system can be used to monitor hydraulic events such as pumping, drilling, etc.
Single hole injection tests	Hydraulic characterization of bedrock and fz.	Scale effects of hydraulic conductivity can be obtained by testing in different scales. Extremely small scales (0.11m) possible to measure. Only small differences between different equipments for K–values 10^{-5}–10^{-8} m/s. Modifications of the test system may have to be made for K larger than 10^{-5} m/s.
Gas–lift pumping	Cleaning of borehole from drilling debris and drilling fluid.	Very limited effect, less than 1% drilling debris recovered. No effect on hydraulic parameters. Can be performed and evaluated as a pumping or interference test. Can be used to achieve high pumping rates in narrow boreholes.
Interference tests	Determination of averaged hydraulic parameters.	Highly applicable for hydraulic characterization of fz and surrounding bedrock. Combination with multi–well, multi–section observation add substantial information regarding heterogeneity and anisotropy. Hydraulic boundaries can be determined. Air–flushing tests (during percussion drilling) difficult to interpret. Monitoring of electrical conductivity and temperature add much information regarding connectivity. Use of tracer during test may improve interpretation substantially

The project has also implied a systematic use of tracer tests for determination of hydraulic as well as transport parameters. In the earlier site investigations tracers were only used for labelling of drilling fluid but the Fracture Zone Project has shown that tracer methods can be used in many more applications such as:

- using labelled drilling fluid as indicator of connectivity and giving rough estimates of transport parameters,
- using tracer methods (dilution tests) for in situ measurements of groundwater flow,
- using tracers in combination with interference tests,
- testing of short-circuiting effects around packers.

In addition to the above mentioned tests, two large scale tracer tests were performed to determine the transport characteristics of Zone 2, the radially converging test and the dipole test. Both tests were shown to be highly applicable for characterization of fracture zones in crystalline rock. New methods and concepts for tracer injection have been developed. Injection without disturbing the flow field and creating dispersive and/or storage effects, that may be misinterpreted, is essential. Multilevel sampling was shown to add substantial information regarding interconnectivity and new tracers like rare earth metal complexes and radioactive tracers were tested. The results of these tests have given important input to the knowledge of flow and transport in fracture zones and also for the design of future tracer tests in crystalline rock.

A summary of the tracer methods used within this project is presented in Table 6-4 together with conclusions from this project regarding their applicability for fracture zone characterization.

Table 6-4 Tracer methods used within the Fracture Zone Project. Summary of aims and comments regarding applicability (fz=fracture zone).

Method	Aim	Comments regarding applicability
Dilution tests	Determination of groundwater flow	Method works well in crystalline rock. Can be applied in a wide range of flows and borehole section lengths, 2-180 m.
Labelling of drilling fluid	Determination of drilling fluid content in water samples. Determination of connectivity of fractures and fz.	Hydraulic connections can be confirmed. Rough estimates of transport parameters may be determined at low costs. Method useful for further tracer test design. Method can be further improved.
Test of short-circuiting effects	Determination of possible leakage around packers.	Method easy to apply. Can be applied in situations where large pressure gradients occur, e.g. pumping in sectionized boreholes.
Combined tracer-interference test	Determination of flow and transport parameters.	Both flow and transport parameters determined under same conditions. Cost effective to combine tests.

Method	Aim	Comments regarding applicability
Radially converging test	Determination of transport parameters	Method good for characterization of fz. New method for injection without excess pressure good but need further improvement. Injection system can also be used for flow measurements and sampling. Multilevel sampling in pumping hole adds vertical component of flow but need further improvement. Stable rare earth metal complexes can be used as conservative tracers in crystalline rock.
Dipole test	Determination of transport parameters	Closed circulation system makes it possible to use radioisotopes. Observation boreholes within the flow field add much information regarding heterogeneity. Large scale dipole implies risk of uncontrolled tracer mass losses.

6.1.5 Geochemical Sampling Methods

Experiences from the site characterization programme has demonstrated a lack of representative groundwater samples for hydrochemical characterization. Therefore, a new technique involving air–percussion rotary drilling in a step–wise way with subsequent groundwater sampling, was tested.

The step–wise sampling made it possible to obtain representative samples only from relatively shallow depths (250 m), due to the high air–pressures needed at depth causing contamination from air intrusion, especially of redox–sensitive parameters.

The collection of representative groundwater samples is a difficult task since there are many sources of contamination during the drilling and initial testing of a borehole. The air–flush technique with step–wise sampling may be a good method for shallow boreholes but for deeper holes, the traditional rotary water drilling with subsequent packer isolation is most likely the best method.

6.2 DISCUSSION AND CONCLUSIONS REGARDING FLOW AND TRANSPORT

One of the main objectives of the Fracture Zone Project was to determine flow and transport characteristics of fracture zones. The investigations have generated a large data base of input data for flow and transport models and a lot of effort has been put into modelling different tests, c.f. Table 5–1. It is clear that the project has greatly improved the understanding of flow and transport in fracture zones. Especially, the importance of low angle and subhorizontal fracture zones has been demonstrated.

The sequence of hydraulic single–hole tests, interference tests, and tracer tests has constituted a good basis for the hydraulical and transport characterization of Zone 2. The intention has been to integrate the results from basic investigations, such as core logging and geophysics, into the planning and performance of the geohydrological programme.

The upper, highly transmissive, part of Zone 2 is very well defined in all boreholes. The transmissivity of the subzone is almost the same over the whole area. Thus, from a hydraulic point of view, the zone appears to be homogeneous. However, the tracer tests and also the core mapping suggest that the transport of solutes occurs more heterogeneously. This is best illustrated by the dipole tracer experiment where tracer travel times differ with a factor 10 between two observation boreholes at approximately the same distance from the injection borehole. Modelling of the dipole test including natural gradient and anisotropy effects suggests that an anisotropy factor of 8 in the direction along the strike of Zone 2 well explains the observed tracer breakthroughs. Both core mapping and tracer tests indicate that the fast transport occurs in only a few well connected flow paths while the slower transport occurs in a network of flow paths. Another important result regarding flow and transport is the near–stagnant flow conditions found in the lower highly transmissive part of the zone.

In summary, the main conclusions regarding flow and transport within Zone 2 are:

- Natural undisturbed groundwater flow is concentrated in the uppermost 0.5 m interval of the zone.

- Induced flow during interference tests and tracer tests is concentrated in 2–5 narrow (0.5–5 m) intervals of extremely high transmissivity, although the entire Zone 2 has a mean width of about 100 m.

- Zone 2 controls the flow in the northern Brändan Block.

- Vertical leakage mainly occurs within the zone and from the bedrock below.

- Groundwater flow rates vary considerably between different parts of the zone and also within the same subzone.

- The high transmissivity and head distribution in the upper bound of the zone prevents fresh water from above from flushing out the old saline water at depth in contrary to the conditions in the southern Brändan Block where fresh water is found at depth.

- The heterogeneity of the zone must be taken into account for transport calculations.

- The heterogeneity in the upper part of the zone may be explained by an anisotropy with a maximum direction along the strike direction of Zone 2.

- Near-stagnant conditions (low hydraulic gradient) prevails in the lower part of the zone.

The flow modelling seems to give consistent results when comparing the efforts made within the project and within the INTRAVAL study. Flow models seem to be able to fairly well predict the average behavior of Zone 2 when introducing a hydraulic disturbance, such as a pumping, to the system. However, in a more detailed scale, the heterogeneity of the system must be taken into account.

To summarize, the numerical simulations have proven to be very useful when analyzing the hydraulic properties of the fracture zone. It has been shown that using the assumed geometry of the flow domain, it is possible to simulate the observed responses of the interference test in the boreholes within Zone 2. However, in the boreholes closest to BFI02 the agreement between measured and simulated responses was not entirely satisfactory.

A comparison of the results from the simulations done after the interference tests with previous modelling efforts indicates that a considerably better understanding of the flow conditions has been gained through the interference tests. The improvements are mainly due to the more detailed description of the flow geometry, which enables a better description of the hydraulic boundaries.

Some comments should be made regarding the certainty of the parameter distribution obtained during the calibration. Using trial and error as a parameter estimation procedure based on data from a single event, one gets essentially no information about the uniqueness of the obtained parameters. More sophisticated parameter estimation schemes may reveal that other parameter distributions also would explain the observed data. One implication of this is that confidence in predictive ability of the model has to be somewhat restricted. Only data from a different hydraulic event (pumping in a different borehole) would enable this particular calibration to be verified.

The sequence of tests and the use of predictive modelling as a design tool has served as a catalyst for the interaction between the modellers and experimentalists involved in the project. The predictive modelling with the 2-D porous medium model has also illustrated that it is possible to predict the head distribution of the system fairly well in the scale beyond 300-500 meters, while in the near-region one has to include local heterogeneities in order to make good predictions. The transport could also be predicted fairly well after the first calibration process. However, the local heterogeneities need to be accounted for. The modelling has also showed that this could be made simply by assigning anisotropy to the system, at least in the upper highly conductive part of the zone.

The regression analysis using simple one dimensional advection/dispersion models have proven to be very useful as a starting point of evaluating experimental data. Especially the effects of variable injection and occurrence of multiple flow paths can be evaluated readily. Such effects are important to understand in order to analyze the breakthrough curves further, where additional transport processes may be needed to account for the unexplained parts of the observed data. It should be pointed out again that supporting field data (other than the breakthrough curve) is essential to the analyses presented for the tracers above.

6.3 RELEVANCE OF LOW ANGLE FRACTURE ZONES IN CONNECTION TO THE SITING OF AN UNDERGROUND REPOSITORY

The Fracture Zone Project has clearly demonstrated that low angle fracture zones are likely to be very important for groundwater flow and long-term bedrock stability. The project has also displayed the difficulty of finding these zones from surface geological and geophysical data and thus, the need for improved methods.

Low angle fracture zones seem to be fairly common, as they have been encountered at most sites investigated in Sweden so far. These observations indicate that at least one low angle fracture zone is likely to be found in the upper 500–1000 m of the bedrock. Thus, it is important to discuss the siting of a repository in relation to such a fracture zone.

Based on the results of this project it seems clear that the location of a repository below a low angle or subhorizontal zone may offer many advantages. The zone acts as a barrier for the groundwater circulation and effectively decreases the hydraulic gradients below the zone /Ahlbom & Smellie, 1989/. If radionuclides reach the zone, a relatively fast transport to the surface will occur but, on the other hand, also a large dilution. Taking the radially converging test as an example of a pumped well scenario, the dilution would be at least 30 000 times. However, in a case where transport occurs under natural gradient, dilution is likely to be smaller. Another advantage may be the shielding effect towards later movements, as reactivations are most likely to occur in the existing fracture zones.

However, one can also foresee possible disadvantages of siting a repository below a low angle zone. The fact that one probably has to penetrate the zone during construction of the repository and thereby create artificial flow paths between the repository and the zone may be a disadvantage. If saline water is present, like in Finnsjön, it is also important that the influence of this water on waste canisters, backfill materials etc. is thoroughly evaluated, as well as the long-term stability of the freshwater/saline interface.

Based on the rock mechanical investigation within this project, the most critical period for future rock stability is during deglaciation of a major inland ice-sheet. Drastically decreased normal stresses may open up low angle fractures and reactivate subhorizontal fractures (sheet fractures) /Rosengren & Stephansson, 1990/, /Leijon & Ljunggren, 1992/.

One of the questions asked prior to the project was whether a safety distance of 100 m from a repository to a fracture zone is relevant or not. The answer to this question is not obvious. From a rock mechanical point of view, a safety distance of 100 m seems to be sufficient /Rosengren & Stephansson, 1990/, /Leijon & Ljunggren, 1992/ but based on the flow and transport characteristics of Zone 2, it is not clear whether this distance is optimal or not. Monitoring hydraulic responses in Zone 2 and in the surrounding bedrock showed that no responses were obtained during air-flush drilling until Zone 2 was penetrated, indicating a low degree of hydraulic coupling between Zone 2 and the bedrock above, which might suggest that a safety distance of 100 m would be enough. However, borehole tests of the bedrock below Zone 2 suggests a much higher degree of hydraulic coupling. Thus, the safety distance will vary accordingly. A fixed safety distance with respect to hydraulic conditions is therefore not adequate. Instead this distance should be determined separately for every fracture zone located within or close to a repository.

The Fracture Zone Project has not been able to determine the transport connectivity between Zone 2 and other zones. This is perhaps the most serious lack of information with regard to the siting of an underground repository in the vicinity of Zone 2 or a similar zone. In order to collect these data, several additional boreholes have to be drilled and more hydraulic interference tests and tracer tests would have to be performed.

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Department of Geology, Chalmers University of Technology and University of Göteborg
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