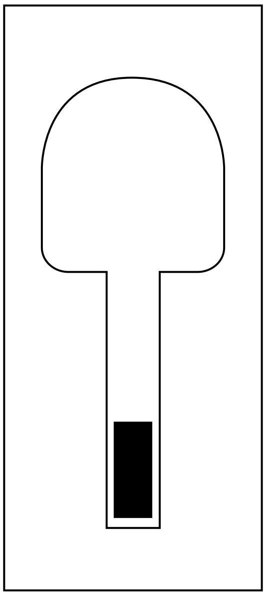
OECD/NEA
International Stripa Project
1980–1992

Overview Volume I



Executive Summary

Charles Fairhurst
Ferruccio Gera
Paul Gnirk
Malcolm Gray
Bengt Stillborg

January 1993

OECD/NEA INTERNATIONAL STRIPA PROJECT

OVERVIEW VOLUME I

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PREFACE

The International Stripa Project was a cooperative research and development project among several member countries of the Nuclear Energy Agency of the Organization for Economic Cooperation and Development. The project, which started in 1980 and ended in 1992, was conducted under the auspices of the Nuclear Energy Agency. The project was managed by the Swedish Nuclear Fuel and Waste Management Company (SKB) under the direction of a Joint Technical Committee (JTC) composed of representatives from participating countries.

The scientific and technical objectives of the project were to investigate several aspects of technology concerned with the feasibility and safety of disposal of long-lived, heat-generating radioactive waste at depth in granitic rocks. In particular, the Stripa Project addressed:

- the development of instruments and procedures to characterize candidate repository sites;
- the understanding and modelling of groundwater flow and solute transport in fractured crystalline rock; and
- the design of engineered barriers capable of contributing to waste isolation by restricting groundwater flow in proximity to the waste containers and in the surrounding host rock.

Because the activities and the results of the Stripa Project have been reported in more than 170 technical reports, the JTC has decided that the final action of the project should be the publication of an overview report that would convey, in relatively concise form, the body of information produced by the project.

The overview report has been subdivided into three volumes:

I. Executive Summary
II. Natural Barriers
III. Engineered Barriers

The Executive Summary summarizes the contents of the other two volumes with the addition of some general considerations about the Stripa Project. The authors of the Executive Summary are the five members of the Overview Reporting Group, that was established by the JTC for the purpose of producing the overview report. The Overview Reporting Group consisted of the two authors of volumes II and III, Paul Gnirk and Malcolm Gray, respectively, and two outside reviewers, Charles Fairhurst and Ferruccio Gera. The Project manager, Bengt Stillborg, acted as coordinator.

TABLE OF CONTENTS

Page

1 INTRODUCTION

The Stripa Project was an international cooperative research effort organized to 1) develop techniques to characterize geologic sites in granite that are potentially suitable for the disposal of heat-generating radioactive wastes, and 2) examine engineered barrier materials and designs that could enhance the long-term safety of a repository system at such sites. The project was jointly undertaken by as many as nine member countries of the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD). The project consisted of three phases, beginning in 1980 and ending in 1992. The Swedish Nuclear Fuel and Waste Management Company (SKB) managed the investigations of the project, carried out principally at the Stripa mine in Sweden, under the direction of a Joint Technical Committee composed of representatives from participating countries.

1.1 GEOLOGIC DISPOSAL OF LONG-LIVED, HEAT-GENERATING RADIOACTIVE WASTE

Deep geologic disposal was first proposed almost forty years ago as a means for isolating high-level and other long-lived radioactive wastes from the biosphere for time periods far in excess of human history. This concept seemed to be an obvious and safe solution to a problem faced by many countries. There are many rock formations that have been geologically stable for millions of years and through which groundwater moves very slowly, if at all. Isolation in such formations seems readily achievable. Out of these initial considerations grew the need to provide convincing evidence that a proposed disposal site and a specific repository design could indeed safely isolate the wastes for many thousands of years. This requires quantitative assessments of long-term repository performance.

In comparison with usual engineering activities, the required isolation time of long-lived radioactive waste is very long indeed. Although there is no international agreement on a single figure for the isolation time required by heat-generating waste, that is, high-level reprocessing waste and spent fuel, a general consensus exists that almost complete isolation should last between several thousand and some hundred thousand years. Comparatively, engineered structures and systems are seldom required to function for more than 50 to 100 years. It is often possible to conduct relatively simple prototype tests over a few months or years to obtain performance data upon which to base reasonable extrapolations over decades. Obviously this approach is not generally applicable to repository design, and a different strategy is required.

Migration of radionuclides from a repository to the biosphere may result from a variety of causes. For a deep repository in a saturated crystalline rock, the mobilization and migration of radionuclides is expected to involve the following three processes:

1) breaching of the buried waste canisters;
2) dissolution or suspension of radionuclides in groundwater; and
3) movement of groundwater and radionuclides through the engineered repository and the host rock.

Access of groundwater to radioactive waste, dissolution of waste form and resistance to groundwater flow and radionuclide migration along the repository excavations and in the surrounding host rock are all amenable to engineered control. To a much larger degree, flow of groundwater through the rock mass is dependent on the natural properties of the rock. It is logical, therefore, to examine the question of geologic isolation of radioactive waste, from the viewpoint of restricting radionuclide migration, by assessing the performance of both natural and engineered barriers.

Although there are many examples of underground excavations in rock, the need to characterize a rock mass in order to assess quantitatively its ability to isolate waste from the biosphere for many thousands of years is an unprecedented undertaking. Some features that may affect critically the ability of the rock mass to isolate waste cannot be measured in laboratory testing (e.g. the geometry and properties of fractures *in situ*). Moreover, because the performance of the engineered barriers will depend on many constraints related to underground construction features, these repository elements must also be studied *in situ*.

1.2 THE INTERNATIONAL STRIPA PROJECT

The considerations cited above led several countries to recognize the need for *in situ* underground testing. This testing would allow the development and evaluation of site characterization procedures and the evaluation of the *in situ* performance of materials for engineered barriers. The high cost of *in situ* experiments and the limited availability of underground laboratories were effective motivations for the initiation of international cooperation and the establishment of the International Stripa Project. The scientific programme completed by the Stripa Project is the result of an evolutionary process covering some thirteen years of work, with shifts in emphasis arising in response to technical findings, administrative needs and changing priorities in the national programmes of participating countries.

The Stripa Project has been successful in demonstrating the use of the observational method for the evolutionary characterization of a volume of crystalline rock and for providing information relevant to the engineering of a repository. Important technical contributions have been made in two main areas:

1) development and demonstrated application of new equipment and methodologies for site characterization; and
2) development and *in situ* evaluation of materials and construction methods for engineered barriers.

In particular, the Stripa Project has achieved important results in the development of:

- methodologies, including techniques and tools, for the geophysical, geochemical and hydraulic characterization of fractured rock;
- procedures for comparing numerical predictions with measurements of groundwater flow and solute transport in fractured rock;
- methodologies to obtain data to assess radionuclide migration in saturated crystalline rock;
- methodologies for characterization of rock masses from the regional to the local scale and for development of conceptual site models; and
- performance evaluation for selected engineered barriers (buffer, backfill, seals), including an appreciation of their longevity.

1.3 SCOPE OF THE EXECUTIVE SUMMARY

The purpose of this executive summary is to summarize the activities and findings of the Stripa Project and, in so doing, highlight its principal achievements in developing and enhancing the technical knowledge that can be used by the member countries for the siting and development of geologic repositories. A significant portion of this executive summary is based on the contents of Volumes II and III of the overview, dealing with the natural barriers, and the engineered barriers, respectively. Information derived from the executive summaries of Phases 1 and 2, the annual reports, and the annual meetings of the Joint Technical Committee has also been used.

The brief history of the Stripa Project is given in Chapter 2. This includes reference to the previous Swedish-American Cooperative programme and the series of organizational meetings that led to the formal establishment of the project. Additionally, the principal objectives of the project and the three phases are cited, along with identification of participating countries in each phase. Chapter 3 summarizes the managerial and financial aspects of the project over its thirteen years of existence. Chapters 4 and 5 present summaries of the principal activities and achievements of the investigations dealing with the natural barriers and the engineered barriers, respectively.

Chapter 6 is a compilation of "lessons learned" over the course of the Stripa Project. These lessons are presented from a technical point of view as well as from an organizational or institutional viewpoint. Chapter 7 highlights, from a rather broad perspective, the conclusions that can be drawn from the technical activities of the project. In addition, some thoughts are presented concerning the focus of future research. Finally, the two Appendices comprise the complete list of acronyms used in the text and a series of definitions, respectively.

2 HISTORY OF THE INTERNATIONAL STRIPA PROJECT

The Stripa mine is located in an old mining district in Sweden, approximately 250 km west of Stockholm. Figure 2-1 shows exactly the location of the Stripa mine. Mining began in the fifteenth century and, during its discontinuous operating lifetime between 1448 and 1976, the mine yielded about 16.5 million tons of hematite iron ore. In 1976, when the ore reserves were exhausted, the Swedish Nuclear Fuel Supply Company (SKBF) leased the mine and the KBS Division of SKBF initiated *in situ* experiments in the granitic host rock. These early experiments were intended to provide preliminary technical data for evaluating the suitability of granite for disposal of high-level radioactive wastes from nuclear power reactors. In the same year, the Swedish-American Cooperative (SAC) programme was established between SKBF and the US Department of Energy (DOE) for the time period 1977 to 1980. During the SAC programme, approximately 400 m of drifts were excavated in the granite and a series of investigations was carried out jointly by the SKBF/KBS Division and Lawrence Berkeley Laboratory (LBL), the latter acting on behalf of DOE. The SAC investigations were concerned principally with: 1) evaluating the response of granite to elevated temperature in a simulated repository environment; and 2) developing techniques for characterizing the hydrological and mechanical characteristics of naturally fractured granitic rock masses.

In late 1978, the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) convened an international seminar in Ludvika, Sweden, on the topic of "*In Situ* Heating Experiments in Geological Formations". The seminar participants discussed an expansion of the cooperative effort at the Stripa mine, after the expected conclusion of the SAC programme in 1980. It was generally agreed that the underground facility provided a unique opportunity for further experimentation in granite to assess the potential for disposal of high-level radioactive wastes in crystalline rock masses. Subsequently, in mid-1979, the OECD/NEA hosted a meeting of potential member countries in Paris for the purpose of discussing topics that might be considered in an international project centred around the Stripa mine. The participants expressed a common interest in *in situ* investigations that would deal with: 1) the characterization of crystalline rock masses by borehole hydrogeological and geophysical techniques; 2) the characteristics of nuclide migration; and 3) the effectiveness of engineered barriers. These topics were discussed further in July 1979 in Otaniemi, Finland, at the "International Symposium on the Underground Disposal of Radioactive Wastes", which was jointly organized by the International Atomic Energy Agency (IAEA) and the OECD/NEA.

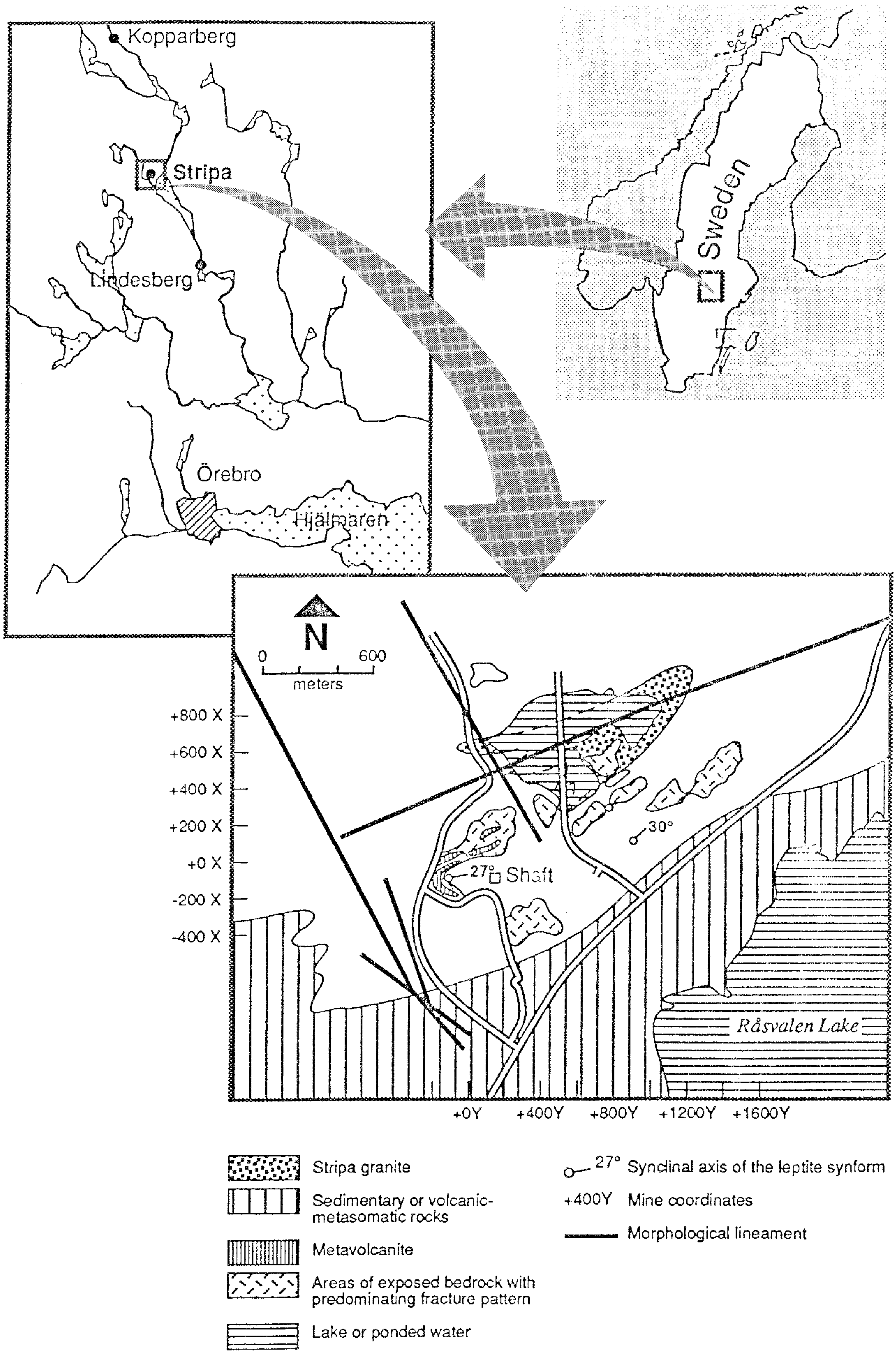


Figure 2-1. Location of the Stripa mine (from Dershowitz et al, 1991).

In November 1979, representatives of Canada, Finland, Sweden, Switzerland, and the United States met in Stockholm. A steering committee known as the Joint Technical Committee (JTC) was established and it was decided that the Stripa Project should be classified as an autonomous OECD/NEA project. Finally, in 1980, these five countries, along with France and Japan, concluded and signed the OECD/NEA agreement, thereby officially beginning what was later known as Phase 1 of the OECD/NEA International Stripa Project. Over a period of thirteen years, the three original topics of interest – 1) hydrogeologic characterization of fractured crystalline rock with minimum disturbance to the rock mass, 2) nuclide migration, and 3) engineered barriers – remained the focal points of the research. The technical review of the investigations was conducted by technical subgroups (TSGs) established by the JTC.

After meetings in January and May of 1982 in Paris, representatives of seven member countries agreed upon the technical content and terms and conditions for a second phase of the Stripa Project. Although the final activities of Phase 1 would not be completed until 1985, Phase 2 began in January 1983. The membership of Phase 2 consisted of the original seven countries, with the addition of the United Kingdom. Spain joined at a later date. The central topics remained the same, but the Phase 2 activities were directed toward the development of improved techniques for characterizing crystalline rock and sealing boreholes and excavated openings.

At a meeting in Sweden in September 1984, the TSGs concluded that further investigations of groundwater flow in fractured rock masses at the Stripa mine should be undertaken only after a review of progress had been made and a comprehensive plan with well-defined goals had been developed . A small group of technical specialists met, over a period of several months, to develop a preliminary proposal of how to integrate site characterization, groundwater flow and nuclide transport, and geochemistry technology in future investigations at the Stripa mine. It was recommended that the investigations should concentrate on a large volume of "undisturbed" rock in the Stripa mine. Additionally, the principal investigator for the borehole and shaft sealing tests was asked to suggest an initial framework for an integrated project that covered the research areas of interest to engineered barriers and rock mechanics.

In March 1985, the TSGs met in Switzerland and fashioned the programme elements for a tentative Phase 3 of the Stripa Project. The duration of Phase 3 was intended to be five years, beginning in 1986. Emphasis was placed on investigations that would integrate the technical knowledge developed in Phases 1 and 2.

In June 1985, the JTC met in Sweden and agreed to proceed with the planning required for a Phase 3 to be developed around the following general objectives:

- To integrate various site characterization techniques and methods of analysis for the prediction and validation of groundwater flow and solute transport in an unexplored volume of Stripa granite.
- To demonstrate and verify the use of different materials and techniques for sealing groundwater flow paths in the Stripa granite.

In August 1985, by direction of the JTC, the project manager and the chairmen of the two TSGs met in Switzerland and developed the programme plan, both technical and budgetary, for Phase 3 of the Stripa Project. The plan identified the following general areas of investigations:

- Site characterization and validation.
- Improvement of site assessment methods and concepts.
- Sealing of fractured rock.

In May 1986, the JTC met in Sweden and 1) approved Phase 3 of the Stripa Project; 2) combined the two TSGs into a single TSG; and 3) established a Task Force on Sealing Materials and Techniques. The Phase 3 participants were Canada, Finland, Japan, Sweden, Switzerland, the United Kingdom and the United States. In 1987, the JTC established a Task Force on Fracture Flow Modelling.

Although the final activities of Phase 2 were not completed until 1988, the Phase 3 investigative efforts began in mid-1986. The field experiments in the Stripa mine were terminated at the end of June in 1991 and all research activities of Phase 3 were completed in early 1992.

3 PROJECT STRUCTURE

3.1 MANAGEMENT

The International Stripa Project, under the aegis of the OECD Nuclear Energy Agency, was based on agreements signed by the participating countries; a separate agreement was signed for each of the three phases of the project. The agreements stated detailed terms and conditions for management and finance and outlined the general scope of the scientific programme.

Responsibility for supervision and financing of the research programme resided with the JTC, which was composed of managers representing each of the national organizations. The JTC also provided information on the general progress of work to the Steering Committee of the OECD Nuclear Energy Agency, through the NEA Committee on Radioactive Waste Management.

A recognized expert (principal investigator) was selected to lead each research activity. In Phases 1 and 2, the design and conduct of the experiments were periodically reviewed by two TSGs. In Phase 3, the two TSGs were combined into one. Also in Phase 3, a Task Force on Sealing Materials and Techniques and a Task Force on Fracture Flow Modelling were established to guide the efforts to seal fractured rock and to evaluate the validity of groundwater flow and solute transport models, respectively. The subgroups and task forces were composed of experts from the participating countries. The organization of the project is illustrated schematically for Phases 1 and 2 in Figure 3-1 and for Phase 3 in Figure 3-2.

The Research and Development Division of the Swedish Nuclear Fuel and Waste Management Company (SKB) acted as the host organization and provided the project management. SKB was responsible for the mine operations and for the procurement of equipment and material for experimental work. Meetings of the TSGs, the JTC, the principal investigators and the project management were held regularly to review the progress of the project.

High-quality scientific work was assured through the recruitment of principal investigators of high standing in the international scientific community. These investigators were assembled into research groups, which conducted all research activities. Continuity of principal investigators and key operational staff minimized delays and disruptions in the scientific programme and led to a high level of motivation of the technical personnel throughout the project.

Owing to the international nature of the project, specific formal quality assurance and control procedures that would be consistent with those of each of the individual national programmes could not be adopted. The quality of the research was assured by reliance on the knowledge and expertise of the individual researchers, the implementation of accepted good scientific practice and thorough documentation of the work. During the course of the project, quarterly progress reports were produced by the various research teams. Over 170 technical reports were issued and many articles were published in the refereed scientific literature.

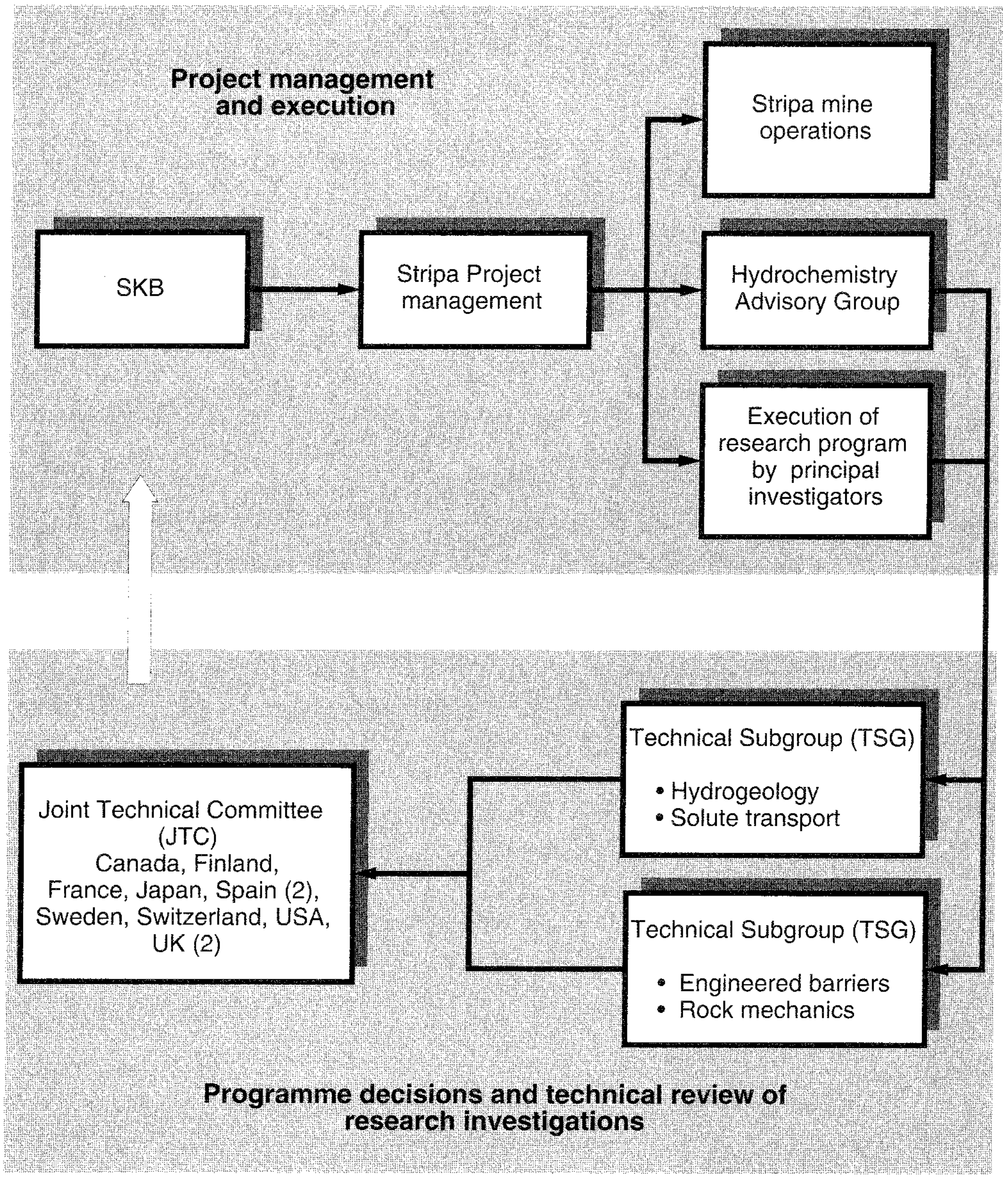


Figure 3-1. Organization of Phases 1 and 2 of the Stripa Project.

At the outset in 1980, four technical subgroups were established to guide investigations in the separate areas of hydrogeology, solute transport, engineered barriers, and rock mechanics. Later that year, the subgroups were reorganized into two subgroups, as shown above, and a separate advisory group for hydrochemistry was established.

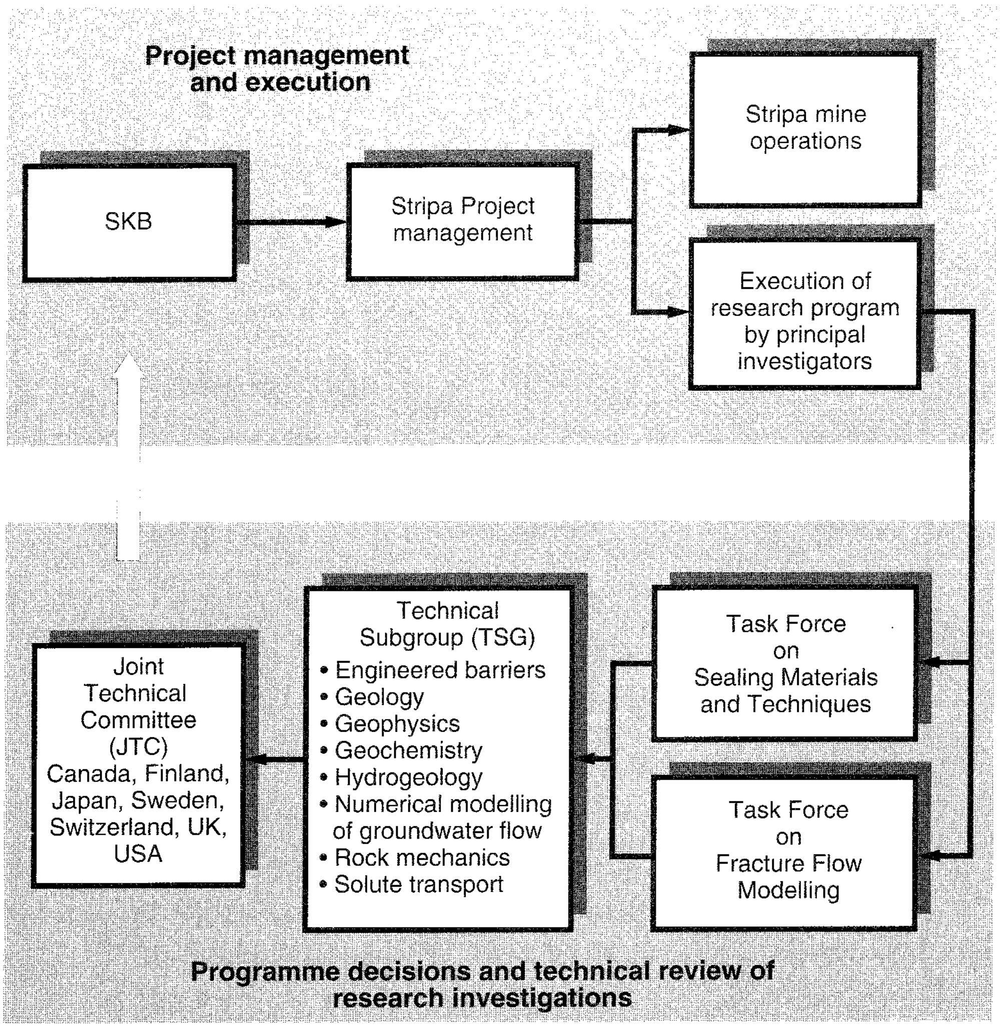


Figure 3-2. Organization of Phase 3 of the Stripa Project.

At the outset in 1986, the JTC combined the two technical subgroups into one technical subgroup, and established a task force to guide the investigations dealing with sealing materials and techniques. In 1987, the JTC established a second task force to guide the activities dealing with groundwater flow modelling. The activities of the Hydrochemistry Advisory Group were then discontinued.

The participants in the Stripa Project and variations in participation in the three phases are shown in Table 3-1.

3.2 FINANCIAL

The participants agreed to assign funds for each of the three phases of the project. In accordance with the signed agreement, the total cost of Phase 3 was adjusted for inflation on the basis of the Swedish Index for Consultants. The remaining budget was adjusted in January of each year. Also, the initial

Table 3-1. Participants in the Stripa Project.

Canada	Atomic Energy of Canada Ltd (AECL Research)
Finland	Teollisuuden Voima Oy (TVO), Imatran Voima Oy (IVO), Ministry of Trade and Industry
France (Phases 1 and 2)	Commissariat à l'Energie Atomique (CEA), Agence Nationale pour la Gestion des Déchets Radioactifs (ANDRA)
Japan	Power Reactor and Nuclear Fuel Development Corporation (PNC)
Spain (Phase 2)	Junta de Energia Nuclear (JEN)
Sweden	Swedish Nuclear Fuel and Waste Management Company (SKB)
Switzerland	National Cooperative for the Disposal of Radioactive Waste (NAGRA)
United Kingdom (Phases 2 and 3)	Department of the Environment (UK DoE)
United States	Department of Energy (US DOE)

cost estimates of Phases 1 and 2 were revised because of changes in the programme of work, as agreed by the JTC, and inflation.

The total cost of the International Stripa Project, Phases 1 to 3, as borne by the participating countries in accordance with the agreements, was as follows:

Phase 1 (1980-1985)	47 MSEK
Phase 2 (1983-1988)	66 MSEK
Phase 3 (1986-1992)	144 MSEK
TOTAL COST	257 MSEK

This total project cost does not account for costs borne by the individual member countries as part of their participation in the JTC, technical subgroups, and task force activities. Also, the total expenditure does not include the cost of a number of technical contributions borne by member countries and provided at no expense to the Stripa Project.

4 NATURAL BARRIERS

4.1 INTRODUCTION

As the search for geological sites for nuclear waste repositories progressed in various countries, several classes of rock formations emerged as preferred candidates. Crystalline rocks, such as granites and diorites, are abundant in many parts of the world and are attractive on at least two counts. The rock strength is high, so that it is easy to construct stable excavations, and the intrinsic rock permeability is low (i.e. the resistance to groundwater flow is high). In many cases, however, the rock mass is traversed by systems of discrete planar fractures that are the consequence of various phases of tectonic activity through geological history. The fractures may range from closely-spaced microfractures that are almost invisible to the naked eye, to extensive fractures and fault systems in which spacing varies from metres to hundreds of metres and more. When these fractures are interconnected, their resistance to groundwater flow may be much lower than that of the intact rock.

Radionuclides carried by groundwater usually move through a rock mass at a different rate than water. The nuclides may be sorbed onto rock fracture surfaces and/or into the rock matrix, depending on the chemistry of the radionuclides, groundwater and rock surfaces; and so may travel much more slowly than groundwater. This might not be the case for radionuclides attached to colloidal suspensions in groundwater. Thus, characterization of groundwater flow and radionuclide transport in fissured rock is clearly a topic of primary importance in assessing the suitability of a particular rock mass for hosting a waste repository.

4.1.1 Groundwater flow and solute transport

The rate of groundwater flow through a rock mass depends on two main factors: 1) the resistance to flow, determined by the characteristics of the constricted pathways through which water flows; and 2) the driving force, usually the "hydraulic gradient".

Most groundwater theory and experience concerns flow in porous, granular materials, where the material structure provides many interconnected pathways and the overall resistance to water flow is essentially uniform, even over a very small volume. This volume, above which there is no significant change in the specific flow resistance (known as the "representative elementary volume"), is a measure of the homogeneity of the material. If the resistance is the same in all directions through the volume, the material is said to be isotropically permeable; if not, it is anisotropic.

In porous rocks under moderate hydraulic gradient, the flow can be described by a simple and well-known linear relationship introduced by Darcy in 1856. In this relationship, the flux is equal to the product of the flow resistance, or hydraulic conductivity, and the hydraulic gradient.

From the viewpoint of hydraulic properties, there are important differences between porous materials and cyrstalline rocks. The latter are formed from a molten rock mass; after solidification, during cooling, they develop thin, flat cracks or fractures of various sizes. Exposure to tectonic forces over geological time can extend these fractures and/or introduce new sets of fractures. Each set is usually planar, with discrete spacing between each fracture, and has a dominant orientation. Some sets may be relatively open and highly conductive, whereas others may have been sheared. The sheared fractures may become filled with fault gouge and may act as barriers to water flow. The hydraulic conductivity of relatively thin planar fractures is much more sensitive to changes in pressure, acting within (fluid pressure) or outside (rock stresses) the fractures, than is the hydraulic conductivity of porous granular media. Such media are formed of aggregated particles and show a more uniformly distributed connected porosity through which water can flow. Moreover, field observations suggest that fractures in crystalline rocks tend to be distributed "log-normally" – that is, with many short, closely-spaced fractures or cracks and progressively fewer, longer and more widely spaced fractures.

How, then, can flow in a fractured rock be characterized? Can a representative elementary volume be assumed, at least for the larger scale regional groundwater flow studies, so that an "equivalent porous medium" may be defined that allows Darcy's law to be used? Is there a scale (e.g., around individual excavations) below which such an approximation is invalid? How do stress changes induced by excavations or by temperature changes in the rock mass affect groundwater flow and transport, and/or the interpretation of *in situ* experimental observations? Can flow in fractured rock be predicted with reasonable accuracy? Can any adverse features of flow in fractured rock masses be improved by appropriate engineering design of the repository? These questions concerning groundwater flow and transport need to be addressed in order to establish the suitability of fractured crystalline rocks as sites for high-level radioactive waste repositories.

To answer such questions, it is necessary to study the behavior of the fractures directly in the rock mass. The investigations in the Stripa Project were designed, in part, with this purpose in mind.

4.1.2 Site characterization

Characterization, in a broad sense, means quantification of the geologic, hydrologic, geochemical and geomechanical characteristics of a rock mass. These characteristics represent a wide range of physical parameters and attributes of the rock, ranging from intrinsic properties such as permeability and electrical conductivity to larger scale conditions and processes such as the regional hydraulic gradient and tectonic activity. The end product of these characterization activities is an understanding of the properties, conditions and ongoing processes within the rock mass as they exist today, as well as an understanding of how such characteristics evolved to their current states.

The preliminary selection of a potential site for a repository for heat-generating radioactive waste may be based only on limited data from regional tectonics and structural geology, as inferred from surface observations supplemented by geophysical investigations and a small number of vertical drill holes. Underground access to a potential repository site adds important and more detailed insight to the general understanding obtained from the initial regional characterization studies. When a large volume of rock is exposed at depth in the horizontal or subhorizontal direction, features that may have major significance, but which the regional study may have missed (e.g., steeply inclined, water-conducting fractures), can be revealed. Underground access also provides an opportunity:

1) to confirm, by direct measurement, the values previously assumed for the properties of the rock mass (e.g., homogeneity, permeability, *in situ* stress state), as well as the characteristics of specific structural features and hydraulic anomalies; and
2) to determine whether the introduction of the repository excavations would lead to local, or more extensive, irreversible effects (e.g., creation of an excavation disturbed zone with enhanced permeability around the periphery of the openings); whether these effects would be exacerbated by the introduction of heat-generating waste; and whether these effects can be addressed sufficiently by engineering measures to ensure that the overall isolation capability of the proposed repository site is not compromised.

4.1.3 Elements of the natural barriers investigations

The Stripa Project was established in recognition of the need for a more comprehensive *in situ* research programme to address critically important basic questions concerning groundwater flow and radionuclide transport related to isolation of heat-generating radioactive waste in fractured crystalline rock. Because several countries were considering the possibility of crystalline rock for waste repositories, an international effort seemed appropriate.

As described in Chapter 2, the Stripa Project developed in three overlapping phases during the period 1980–92. For the Natural Barriers investigations, these phases were (also shown in Figure 4-1):

Phase 1 (1980–85). A learning exercise to evaluate the possibilities and limitations of existing characterization methods and experimental techniques.

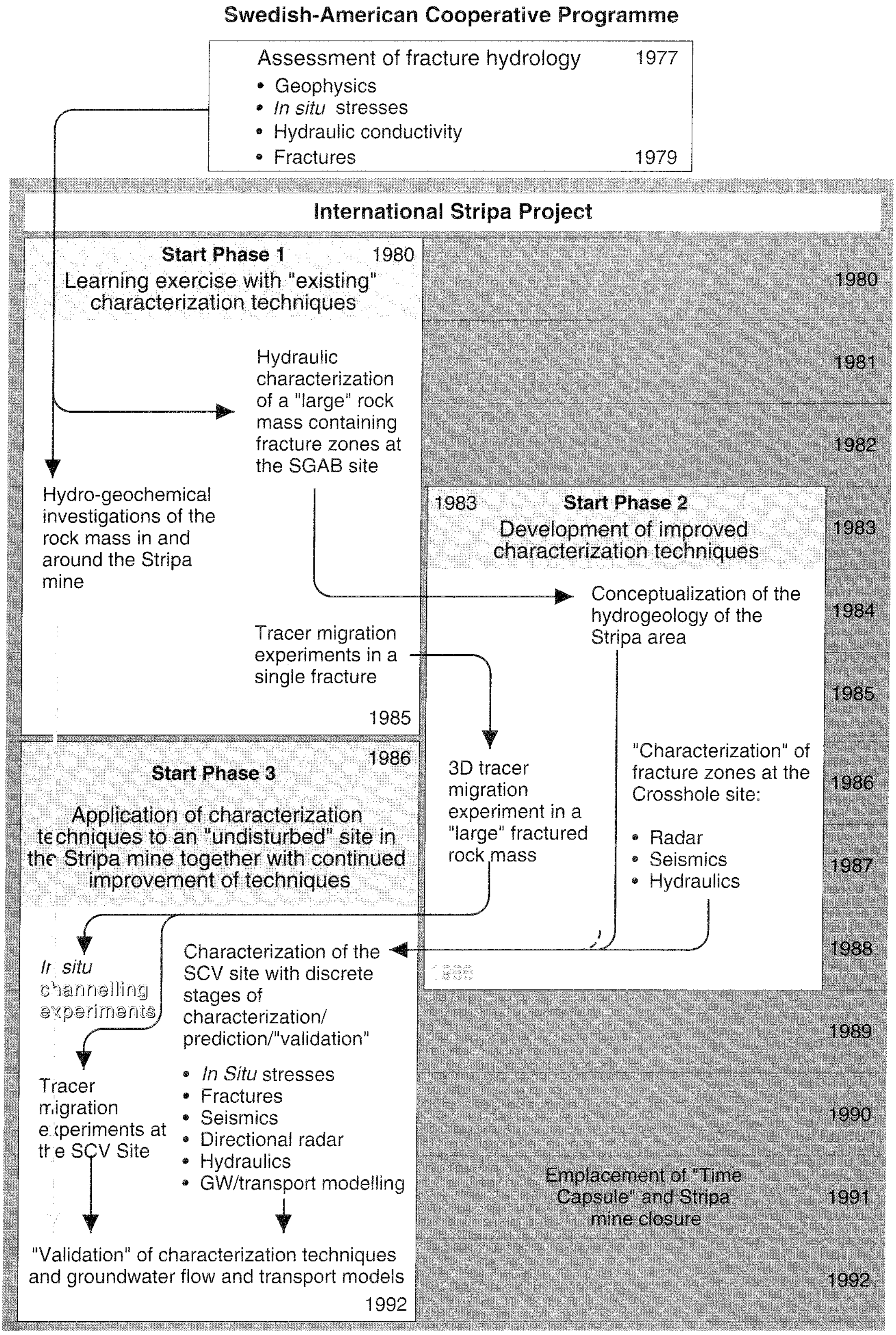


Figure 4-1. Evolution of the characterization, geochemistry, tracer migration, and modelling activities during the Stripa Project.

The development of conceptual hydrogeologic models at Stripa began during Phase 2 and was continued as a significant component of Phase 3.

Phase 2 (1983–88). Development of improved characterization procedures and techniques.

Phase 3 (1986–92). Application of characterization procedures and techniques involving: (i) hydrogeologic characterization of the SCV (Site Characterization and Validation) site in the Stripa mine; and (ii) predictions of groundwater flow and transport in the SCV site, and comparison of predictions with observations.

Within the various phases, three parallel component research activities can be identified:

1) *Characterization of the groundwater flow system,* on both the **regional scale,** within which the mine was situated, and a **local scale,** within the mine itself. The regional-scale system was simulated by means of a hydrogeologic equivalent porous media (EPM) model. The calculated flow system was confirmed by comparison with mine pumping rates and by "isotopic" dating of groundwater. The local-scale models considered flow through discrete fracture systems, with predictions of flow into the boreholes in the SCV block and, later, into the SCV drift.
2) *Development of non-destructive in situ tests* for locating and characterizing discrete fracture zones within a crystalline rock mass. The tests were based on radar, seismic and hydraulic techniques and also involved both regional- and local-scale studies.
3) *Investigation of the solute transport properties of rock fractures in granite.* This activity involved tracer migration experiments in single fractures and fracture systems, and studies of channelling of flow within fractures.

All three components were brought together in the SCV programme, which concluded the Stripa Project. The progression of the various components is described below, following the outline shown in Figure 4-2.

4.2 REGIONAL-SCALE SITE CHARACTERIZATION

The Stripa mine had operated since the middle of the fifteenth century, and the general geology of the rock mass in and around the mine was well documented. Taking advantage of the existing background information, the project investigations were focussed on evaluating the main structural features of the geological setting. These features were the discrete zones of intensive fracturing in the granite, and systems of less intensive fracturing contained within the rock between the discrete fracture zones. The current groundwater hydrology and its associated geochemistry are products of the disturbance induced by the mining activities over many years, together with the groundwater conditions at the surface and in the surrounding rock masses. Similarly, the state of stress in the rock mass had been influenced by the mined excavations. Thus, when the Stripa Project began in 1980, the

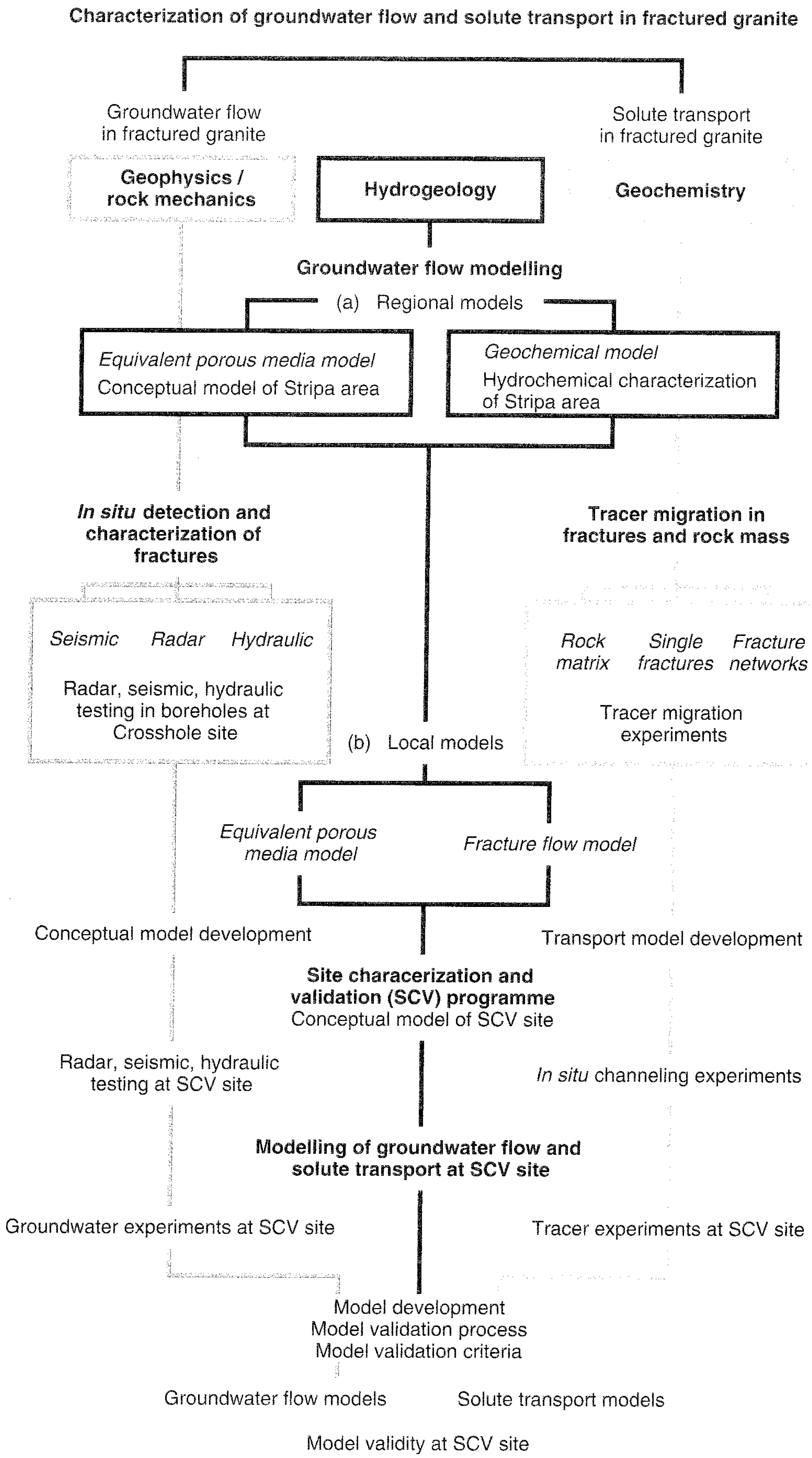


Figure 4-2. Relationships among the natural barriers investigations.

natural state of the rock mass had accommodated the disturbances induced by underground mining over several centuries.

4.2.1 Conceptual model of the Stripa area

The conceptual model of the hydrogeology of the Stripa area was based on information obtained from pre-Stripa-Project studies and from data collected during Phases 1 and 2 (Gale et al, 1987). These geological, geochemical and hydrologic data were gathered by means of 1) observation of drill cores and exposed rock on the surface and in the Stripa mine; 2) laboratory tests of the groundwater geochemistry and rock fracture characteristics; and 3) hydraulic tests in boreholes drilled from the surface and at various locations within the Stripa mine. On the basis of the geologic and hydrologic data, a 3-D finite element model of the Stripa area, including the Stripa mine, was developed and calibrated against the rate at which groundwater was pumped out of the mine and against groundwater transit times inferred from the isotope studies. This finite element model, which represented the average rock and the fracture zones as equivalent porous media (EPM) with different hydraulic properties, covered a volume of rock with a plan area of about 100 km^2 and a depth of 3 km. In addition, several successively smaller sub-models were developed to represent in greater detail the rock mass that contained the rock excavations within the Stripa mine. These models were used in Phase 3 to obtain the hydrologic boundary conditions around the SCV site in order to support modelling of the groundwater flow and transport within the site.

The calculated inflow to the Stripa mine was within 10% or less of the measured pumping rate, which was good agreement, considering the large dimensions of the modelled region and the relative sparseness of subsurface geologic information and hydraulic data. The quantification of the hydraulic conductivity of the rock mass as a non-linear function of depth, together with the inclusion of the significant fracture zones, were important features of the model. Assumptions of a depth-independent hydraulic conductivity and different bedrock units produced inflow rates to the mine that were considerably less than the pumping rate. The computed hydraulic gradients within the vicinity of the mine were consistent with measurements made in surface boreholes, and the discharge points of groundwater were consistent with the locations of lakes in the area. The general pattern of head isopotentials indicated that groundwater recharge and shallow groundwater flow within 3 km of the mine influenced the groundwater discharge into the deepest levels of the mine. This result supports the hypothesis, based on geochemical data, that mixing of shallow and deep waters occurs in some regions of the mine.

The computed travel times of the groundwaters through the rock mass at Stripa were much shorter than those based on interpretations of geochemical and isotopic data. However, groundwater flow models based on equivalent porous media models are known to predict fluxes more accurately than travel times.

4.2.2 Hydrochemical characterization of the Stripa area

In 1980, a Hydrochemistry Advisory Group (HAG) was established to determine the origin and evolution of deep groundwaters within the Stripa granite through the study of their geochemistry (Davis and Nordstrom, 1992). In addition, the HAG was asked to identify processes and mechanisms of water-rock interactions that might occur at the depths being considered for the disposal of heat-generating waste in crystalline rock. Between 1985 and 1988, water samples were collected from packed-off water-bearing zones in boreholes within the Stripa mine. The water samples were subjected to routine and specialized analyses by the HAG members at various laboratories in Europe and North America. Results indicated that the salinity in the groundwater at Stripa was not caused by the presence of ancient sea water. The composition of the groundwater could not be matched with that of sea water, even after reasonable allowances were made for dilution and ion exchange. Studies of the rubidium-strontium chronology and the ^{87}Sr to ^{86}Sr ratios of rocks, minerals and fluids suggest that the Stripa granite was intruded 1.71 Ga (1 Ga = 10^9 years) ago and that later hydrothermal activity, perhaps 1.63 Ga ago, formed moderately high-temperature minerals along fractures. Isotopic ratios indicate that sea water diluted by groundwater, in a mixture very depleted in rubidium and strontium, invaded the granite along fractures, probably less than one million years ago.

This was the first time that many techniques had been used in a single study to determine the origins and ages of groundwaters. These techniques included isotopic disequilibrium, buildup of radiogenic gases, decay of cosmogenic radionuclides, buildup of *in situ* generated radionuclides, and matching changes in concentrations of stable nuclides with known climatic fluctuations. A noteworthy achievement of the research work at Stripa was the clear demonstration, for the first time, that a number of so-called "cosmogenic radionuclides" are generated in the subsurface in quantities that greatly exceed the cosmogenic components. *In situ* production of the "key radionuclides" ^{36}Cl, ^{37}Ar, ^{39}Ar, ^{85}Kr, and ^{129}I takes place in the granite at Stripa at rates that exceed the atmospheric production of these radionuclides. The concentration differences between the *in situ* and atmospheric production are indicative of groundwater "residence time". Additionally, measurements were made of the stable nuclides ^{2}H, ^{18}O, ^{34}S, ^{37}Cl, ^{40}Ar, and ^{87}Sr, as well as the unstable nuclides identified above, together with ^{3}H, ^{14}C, ^{226}Ra, ^{234}U. A large number of these measurements were difficult to make with existing analytical techniques owing to the low concentrations and slight differences among samples from different locations and because the constituent had never, or only rarely, been measured before. The HAG finding that ^{36}Cl can be produced *in situ*, while previously it was thought to be generated only by the action of cosmic radiation in the atmosphere and by nuclear explosions, was particularly significant. This radioisotope can be used to measure the natural neutron flux in the subsurface.

The cross-section of the Stripa area (shown in Figure 4-3) illustrates the pattern of groundwater circulation and the residence times, interpreted from the presence of stable and unstable nuclides. The upper 300 to 400 m of the

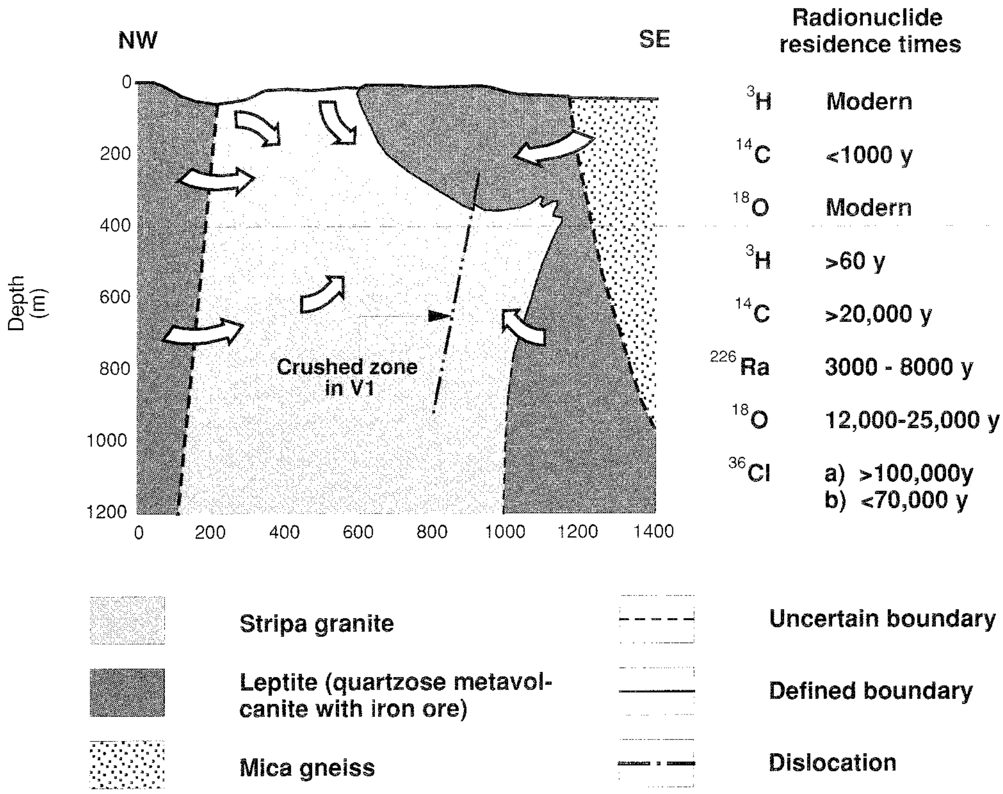


Figure 4-3. Regional model of hydrochemical conditions at Stripa (Gale et al, 1987).

Shallow water and deep water are drawn into the area of the mined openings, forming a mixed water.

Stripa granite have been invaded in various locations by modern surface waters, small amounts of which have penetrated deeper than 800 m. Concentrations of ^{14}C in dissolved organic and inorganic carbon indicate an isolation time of several thousands of years, particularly for the relatively deep groundwater. Dissolved chloride at depths of 300 to 600 m, and possibly deeper, has migrated into the granite from the surrounding metamorphic rocks. Below 600 m, the residual concentrations of ^{226}Ra and ^{36}Cl suggest that most of the water has been isolated from the atmosphere for at least several thousands of years and possibly as long as a few hundred thousand years, even though lateral migration of the water has taken place.

In the view of the HAG, the use of geochemistry to predict the long-term movement of radionuclides over distances of several kilometres is not a straightforward characterization method, especially for fractured rocks of plutonic origin. The presence of brackish groundwater, or water with a high pH or high helium content, indicates a rather "static" groundwater system. These kinds of geochemical conditions do not develop rapidly and suggest, qualitatively, that the ages of such waters would be of the order of thousands of years. The most reliable quantitative indicators of water age and, correspondingly, rates and directions of regional groundwater flow are ^{3}H, ^{14}C, ^{39}Ar, and ^{36}Cl, provided that the chemistry of the stable elements is understood and the *in situ* production of the radionuclides is minimal or quantifiable.

4.3 LOCAL-SCALE SITE CHARACTERIZATION

The need to develop tools and methods to evaluate the hydrogeologic characteristics of fractured rock masses was recognized from the start of the Stripa Project. The emphasis was placed on development of remote sensing techniques in boreholes; so that the minimal disturbance of the natural state of the rock during testing would permit to obtain data reflecting *in situ* conditions. This approach offers great promise for the cost-effective exploration of the large volumes of rock required for geologic disposal sites. The data collected by remote sensing from a few strategically placed boreholes could be used to make a preliminary assessment of the suitability of the site for long-term containment of radioactive waste, and to guide additional studies in evaluating specific features and anomalies.

4.3.1 Conventional characterization techniques

In Phase 1, the characteristics of fractures from drill core and from observations in boreholes and drifts were determined using conventional techniques (Stripa, 1986). A televiewer was used to scan the walls of boreholes to determine fracture locations and orientations, complementing the core-logging observations. In Phase 2, a more comprehensive description of the fracture systems in the Stripa granite was developed (Stripa, 1989). This description was based on information obtained previously from core logging, borehole televiewer scans and fracture mapping in the various drifts; it was enhanced during the remainder of the project with additional borehole and core data and drift mapping. The compressive strength and elastic deformation properties of the granite were obtained by laboratory tests on drill core and by an *in situ* block test in the mine. The influence of normal and shear loadings on those fracture characteristics relevant to water flow through the fractures, as well as aperture variations within fracture planes, were investigated in the laboratory, using large-diameter drill cores obtained from the mine. *In situ* stresses were measured in boreholes at various locations in the mine, using overcoring and hydraulic fracturing techniques.

4.3.2 Remote sensing techniques

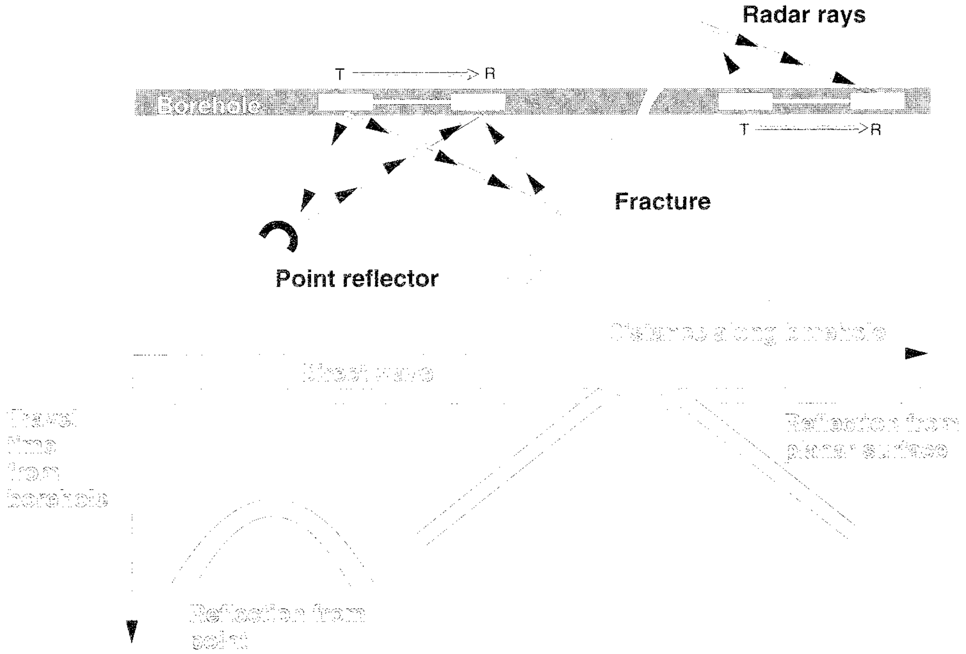
In Phase 2, a programme was undertaken to develop remote sensing techniques based on radar, seismic and hydraulic testing, and requiring only a few boreholes, for the detection and characterization of fracture zones (Olsson et al, 1987a). These methods can provide data on the electric, elastic and hydraulic properties of rock, including, specifically, the geometric characteristics and the water flow properties of the fracture zones. The results of hydraulic testing initiated in Phase 1 provided a basis for design of the Phase 2 activities, including the selection of the borehole array and testing objectives. Much of the development and testing of these methods was carried out at the SGAB (Swedish Geological Company) site and, later, at the Crosshole site, as described below (Figure 4-6).

Radar testing

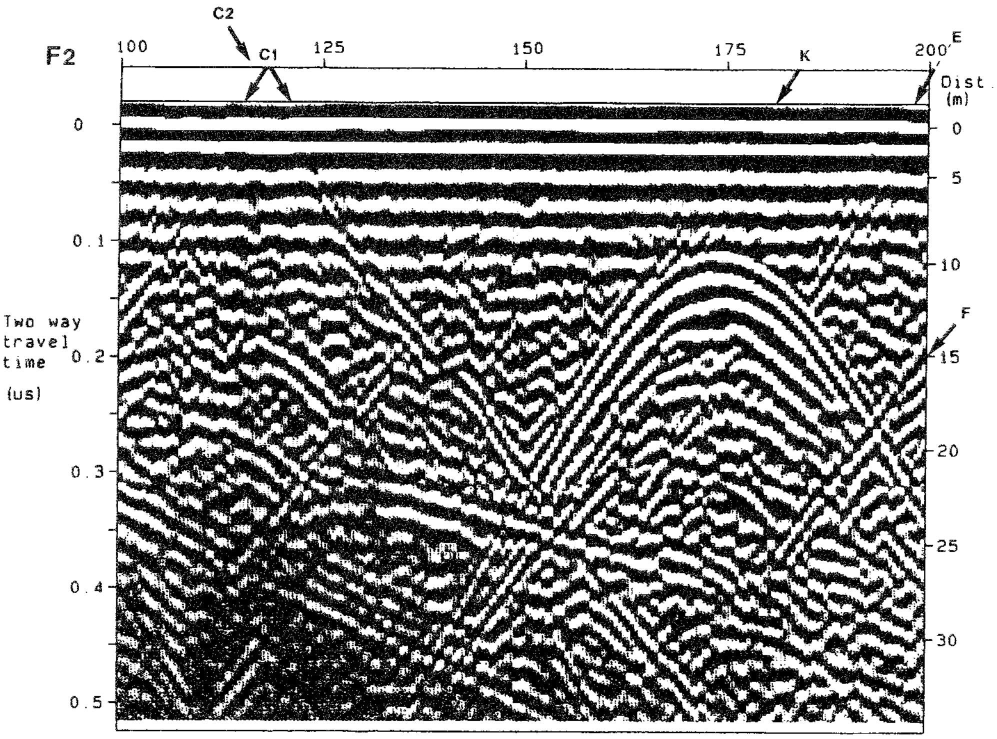
Between 1983 and 1985, the radar system was developed and designed for field work on a production basis. Since then, the system has been used to conduct borehole surveys at more than 25 sites throughout the world in a variety of rock types (Olsson et al, 1987b). This short-pulse radar system, which is capable of both single borehole and crosshole measurements, displays and processes the data directly in the field. The radar senses localised changes in the dielectric constant and electrical conductivity of the rock mass usually associated with the increased water content of fracture zones. A schematic of the operation of the radar system and an example of a radar scan are shown in Figure 4-4. The location and geometric characteristics of the fracture zones at the Crosshole site, as determined by the radar technique, were consistent with interpretations based on crosshole seismic data. A directional antenna developed for the radar system in Phase 3 made it possible to determine the orientation of fracture zones from measurements in a single borehole.

Seismic testing

The crosshole programme included the development of large-scale and small-scale crosshole seismic techniques (Cosma, 1987; Pihl et al, 1986). The crosshole seismic technique, as illustrated in Figure 4-5, involves the placement of a chain of receiving units in one borehole, and the detonation of an explosive source, or impact by a mechanical device, in a second borehole. The location and geometric characteristics of fracture zones existing between the boreholes can be derived from the results of tomographic inversions of the travel-time data. The small-scale crosshole seismics tests at the Crosshole site produced a detailed image of the structure between boreholes. In contrast, the large-scale tests performed at the Gideå site, located in northern Sweden and consisting of a migmatized gneiss with distinct fracture zones and dolerite dikes, revealed only the major structural features. In Phase 3, the seismic techniques were improved through the development of a reflection technique to determine the location and orientation of structural features, using a high-frequency seismic source located in a borehole. "Image source" theory and travel-time / distance profiles obtained with different seismic source/receiver locations were used to determine the feature orientation. The geometric characteristics of fracture zones within the plane can be identified by tomographic analysis from the amplitude and velocity profiles obtained from a number of different detector and source locations.

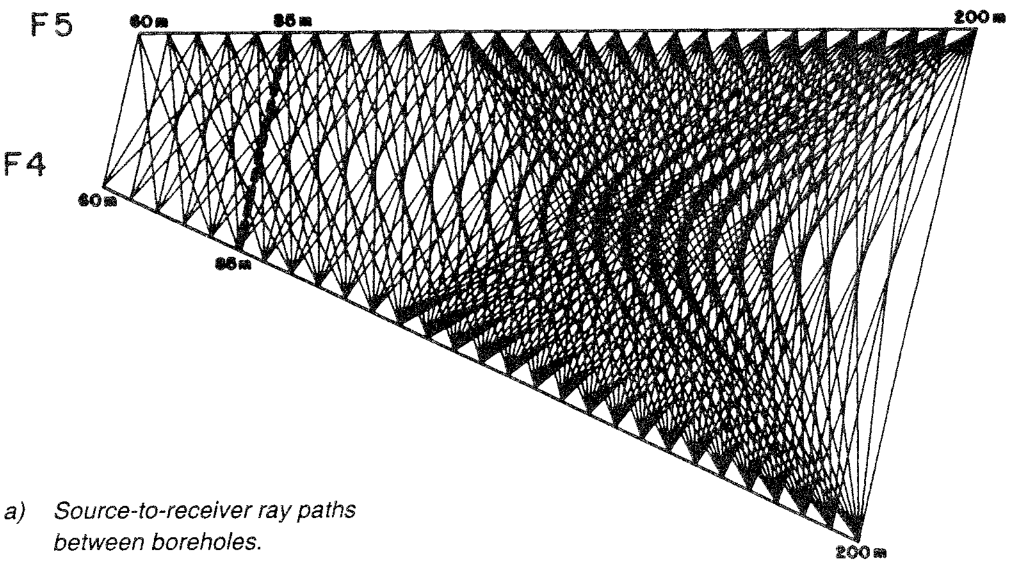


a) *Scheme of the borehole-radar testing configuration with characteristic patterns generated by reflections of the electromagnetic waves by a planar surface and a point.*

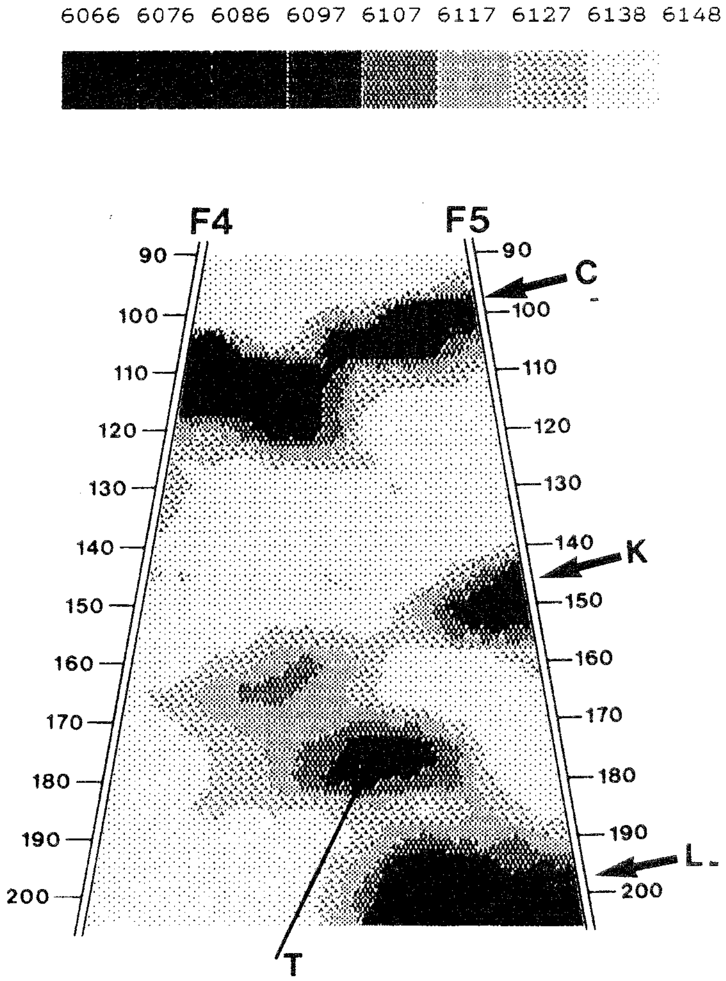


b) *Radar reflection map from measurements in borehole F2 at the Crosshole site. C1, C2, K, E and F indicate fracture zones in the granitic rock mass.*

Figure 4-4. Borehole radar testing method (Olsson et al, 1987b).



a) Source-to-receiver ray paths between boreholes.



b) P-wave tomographic reconstruction of plane section between boreholes at the Crosshole site. C, K, L and T indicate fracture zones in the granitic rock mass.

Figure 4-5. Borehole seismic testing methods (Cosma, 1987).

Hydraulic testing

Throughout the crosshole programme in Phase 2 and the SCV programme in Phase 3, determined efforts were made to integrate the hydrologic investigations with those involving remote-sensing geophysical techniques. The aims of the hydraulic testing were to measure the distribution of hydraulic properties within extensive fracture zones and to determine the hydraulic connections between fractures zones. The computer-controlled hydraulic equipment for single-borehole testing and crosshole sinusoidal hydraulic testing provided, on site, real-time interpretation of the data (Black et al, 1987). In addition, methods of analysis were developed to obtain information on the geometries of flow channels within fracture systems from single-borehole packer-test data.

4.3.3 Crosshole site programme

The Crosshole site, shown in Figure 4-6, was located on the 360 m level of the Stripa mine and consisted of a rock mass defined by six boreholes, drilled from the end of the drift in a fanlike array, to outline a tilted pyramid with a height and base of about 200 m. The site encompassed 3 million m^3 of fractured, granitic rock and was used for testing a variety of characterization methods (Olsson et al, 1987a). Radar, seismic and hydraulic tests were conducted in the six boreholes in both the single-borehole and crosshole modes. A combination of single-borehole radar reflection measurements and tomographic inversion of crosshole radar and seismic data were used to define the geometrical characteristics of four major fracture zones, as well as several other less prominent zones, within the site.

The head distribution and hydraulic conductivities of the rock mass were determined by, first, evaluating regions of major groundwater flow with single-borehole hydraulic tests; and then comparing the results with those obtained from the single-borehole radar reflection tests in order to identify regions where anomalous features could be investigated by crosshole hydraulic testing.

The collected results from the fracture analysis of the core logs and the remote sensing tests in the boreholes provided the basis for developing a conceptual model of the hydrogeology of the Crosshole site. Furthermore, the applicability and effective "dimension" of the characterization methods were evaluated, as given in Table 4-1. The ordering in the table indicates the hierarchy of test methods that might be considered for sequential determination of the hydraulic characteristics of a saturated granitic rock mass. This hierarchy is representative of the increasing dimension of measurement, as well as the increase in time required for testing and data interpretation.

The research at the Crosshole site demonstrated that it was possible to characterize the geologic and hydrologic features of a saturated, fractured granitic rock mass of some 3 million m^3 and to define its hydrogeology more reliably and realistically than had been thought possible previously.

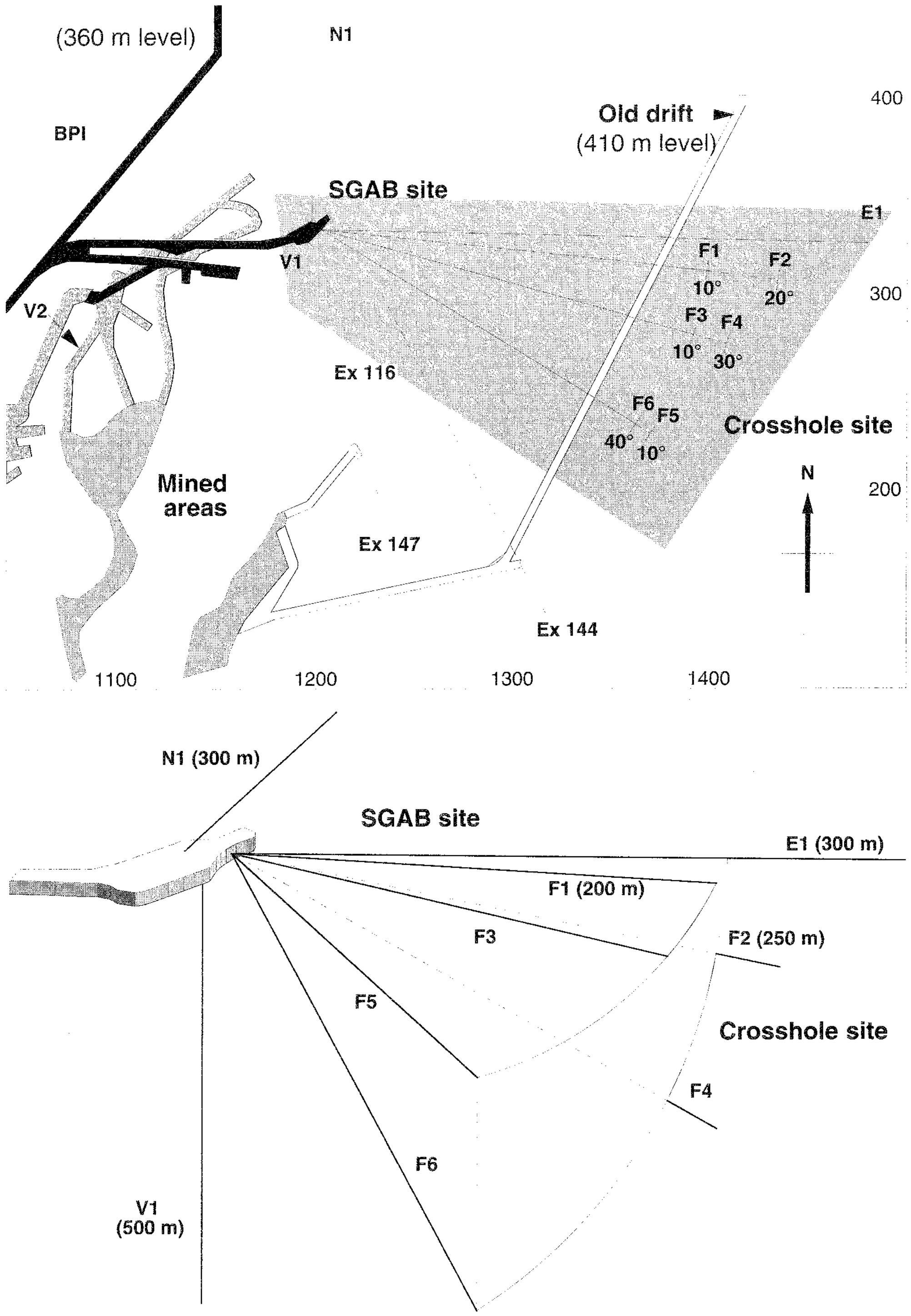


Figure 4-6. Plan and perspective views of the borehole arrays at the SGAB and Crosshole sites (Carlsten et al, 1985; Black et al, 1987).

The SGAB site was used for the hydraulic investigations in Phase 1 and the Crosshole site for the radar, seismic, and hydraulic investigations in Phase 2. All of the boreholes were drilled from the end of a drift located on the 360 m level.

Table 4-1. Applicability and effective "dimension" of characterization methods used at Crosshole site (modified after Olsson et al, 1987).

Characterization technique	Primary information	Secondary information	Dimension of measurement
Logging of rock core	Geometrical features of rock mass	Fracture characteristics	1D
Laboratory tests on rock core	Physical properties of rock matrix	Fracture properties	1D
Single-borehole geophysical logging	Electrical properties of rock matrix/mass	Borehole deviation	1D
Single-borehole hydraulic test	Hydraulic properties of rock mass/fracture zones	Geometrical features of fracture zones	1D (minor 3D)
Crosshole radar and seismic tests	Geometrical features of rock structure	Transport properties	2D - 3D
Crosshole hydraulic tests	Hydraulic properties	Geometrical features of fracture zones	Pseudo 3D

The programme illustrated the value of a well-coordinated characterisation effort, in which geophysical test results provided guidance for subsequent hydrologic testing of those regions of the rock mass containing hydraulic conduits. The investigations resulted in the development of a hierachy of test methods that could be applied sequentially to characterize a site containing water-bearing fracture zones.

4.3.4 Tracer migration experiments

In Phase 1, a groundwater tracer test was conducted in a single fracture in granitic rock that intersected a drift on the 360 m level of the Stripa mine (Birgersson et al, 1992). The purpose of the test was to investigate the sorption and retardation of radionuclides during transport by natural water flow through the fracture over distances of 5 to 10 m; and, concurrently, to evaluate the extent and influence of channelling within the fracture plane. Non-sorbing tracers, used to characterize the water flow within the fracture, were injected from boreholes drilled into the fracture and collected in short sampling holes drilled into the exposed fracture in the drift. The shapes of the breakthrough curves could be interpreted in terms of the presence of channels of different transport lengths. Because the experimental data fit equally well various mathematical models of transport that incorporate matrix diffusion and channelling separately, the transport mechanism, or mechanisms, could not be uniquely determined. Subsequently, six sorbing tracers were injected into the fracture plane. These tracers did not reach the sampling holes during the test period, so portions of the fracture were excavated and tracer concentrations in the rock were measured. It was found that the tracers had diffused into the rock matrix to depths of several mm or more near the injection point.

In Phase 2, a large-scale "three-dimensional" tracer experiment was designed and conducted (Birgersson et al, 1992). The purpose of this experiment was to determine the flow porosity and the dispersion characteristics of a large fractured mass of granite and to investigate further the features of channelling. A 100-m-long drift with small side drifts forming a cross, as shown in Figure 4-7, was excavated at the 360 m level in the mine. Tracers were injected continuously for more than 1.5 years at nine points in three vertical boreholes at distances up to 55 m in the roof, and flow into the drift was collected in plastic sheets glued onto the roof and the upper part of the walls of the drift. The average travel times from the injection points to the plastic sheets varied between 85 and 290 days. The flow porosity of the granite within 10 m of the drift was about double the flow porosity of the relatively undisturbed rock. The apparent combination of independent pathways in the rock and fractures interconnected by channels resulted in quite variable flow rates, making it difficult to determine the dispersivity characteristics of the flow system.

The results of this large-scale tracer experiment supported the view that some fraction of the groundwater flow took place in discrete channels outside the fracture zones that had been previously identified as the main conduits. *In situ* tests were therefore conducted in the Stripa mine in Phase 3 specifically to address the geometric and hydraulic aspects of channelling in single natural fractures. The data from the single-borehole tests, over fracture lengths of about 2 m, provided information on the transmissivity and correlation lengths of conductive fractures and their possible relation to local fracture aperture values, as well as the distance between channels and the widths of channels within fractures. Pressure pulse tests and tracer tests with the "multipede" borehole-injection system provided information on the interconnection and mixing between channels, longitudinal and transverse dispersion, and residence volumes. The test data indicated that, on average, 25% or less of the natural fracture plane was open to water flow during inflow to the open excavation. The channel widths ranged from a few millimetres to a decimeter, and occurred in clusters that were decimeters wide and separated by distances of 0.5 m to 1 m.

From the results of the three series of tests described above, two very important conclusions can be derived.

1) The existence of channels in natural fractures seriously complicates the analysis of tracer transport data. It is difficult to identify the mechanisms of nuclide retardation and to quantify the pathway lengths and the dispersivity characteristics.

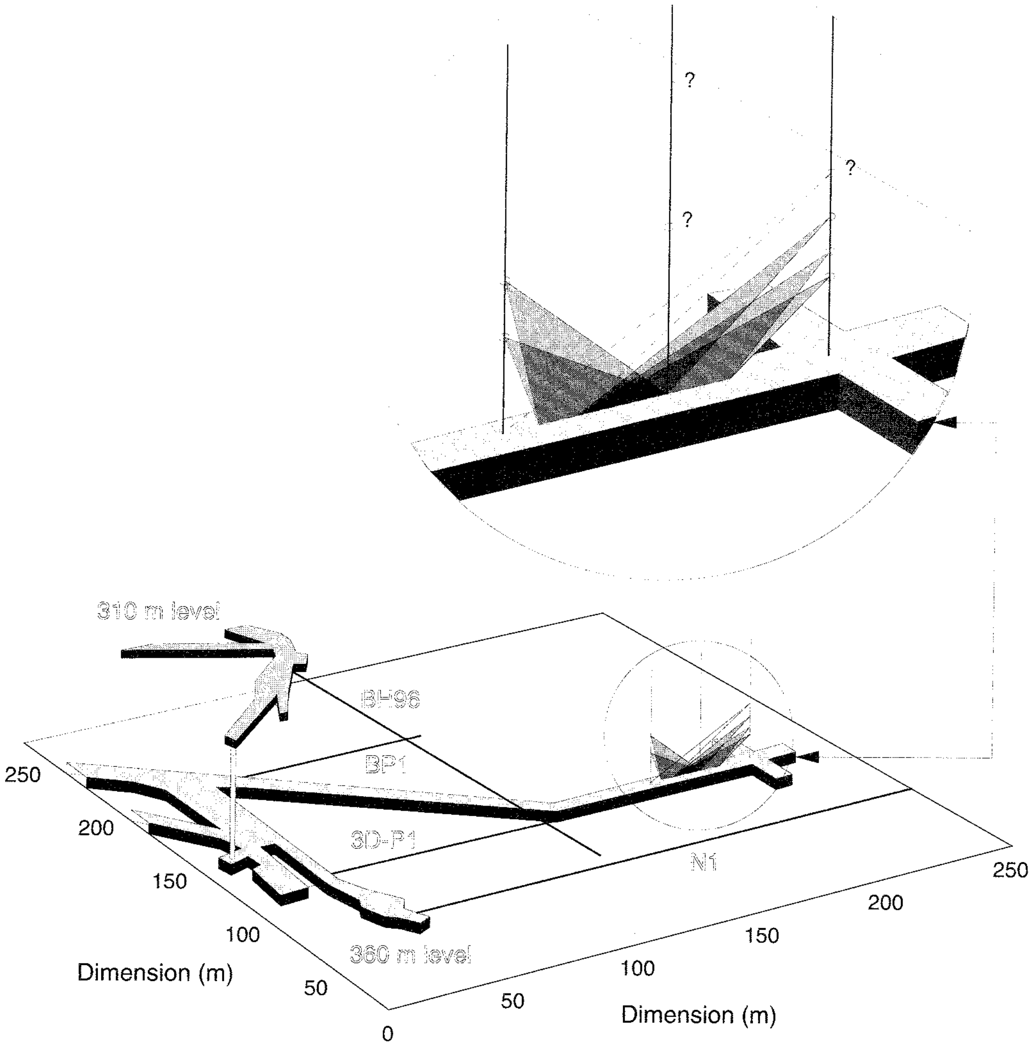


Figure 4-7. Schematic diagram of the configuration of the 3D migration experiment (Birgersson et al, 1992).

The shaded areas indicate the locations at which tracers were observed in the drift.

2) The characteristics of the groundwater flow field and the migration pathways in a volume of rock must be carefully quantified before conducting an *in situ* tracer test. This level of understanding is necessary in order to be able to properly analyze the tracer test data.

In Phase 3, considerable effort was expended to define the geometric and flow characteristics of the H fracture zone at the SCV site by radar and hydraulic testing before initiating the tracer experiment in that fracture zone.

4.4 SITE CHARACTERIZATION AND VALIDATION PROGRAMME

In Phase 3, the Site Characterization and Validation (SCV) programme was undertaken to develop and apply an advanced site characterization methodology that integrated different tools and methods in order to (Olsson, 1992):

- predict the distribution of groundwater flow and transport pathways in a specific volume of fractured Stripa granite;
- support the efforts to develop flow and transport models for fractured rock; and
- evaluate the validity of such models at the SCV site in the Stripa mine.

The SCV site encompassed a previously undisturbed block of granite located about 100 m north of the old mine workings and between the 360 m and 410 m levels. The dimensions of the block were approximately 125 to 150 m on a side and 50 m high, representing a volume of about 1,000,000 m^3.

The SCV programme was subdivided into five stages so that field data could be progressively compared with numerical predictions. The programme included several experiments, as summarized in Table 4-2.

In Stage I ("preliminary site characterisation"), three 200-m-long (S to N) and two 150-m-long (E to W) near-horizontal boreholes were drilled into the SCV block from the 345 m and 357 m levels. A preliminary database on existing fractures was established from core logging, borehole imaging, crosshole radar and seismic testing, and single-borehole hydraulic testing.

In Stage II ("preliminary prediction"), a hydrogeologic model of the SCV site was developed on the basis of the preliminary database. Assessments were made of the geometries and physical properties of the major fracture sets, along with numerical predictions of groundwater flow into six 100-m-long parallel boreholes known as D boreholes. Five of these boreholes were drilled at approximately equal spacing around the circumference of the planned circular cross-section of the Validation Drift. The sixth hole was drilled along the axis of the future drift. It was during this stage that the major fracture zones A,B, D, H, I, J, K, M were identified definitely at the SCV site.

In Stage III ("detailed characterization and preliminary validation"), the groundwater inflow to the D boreholes was measured and compared to the numerical predictions made in Stage II. In addition, three boreholes, referred to as C boreholes, were drilled into the central portion of the SCV site to check the accuracy of the hydrogeologic model developed in Stage II, and to obtain additional radar and seismic data. Finally, crosshole hydraulic tests were performed in the D boreholes and in a combination of the C boreholes and the boreholes drilled in Stage I.

Table 4-2. Experiments conducted at the SCV site in support of the model validation activities in Phase 3.

Experiment	Measurements	Purpose
"First" simulated drift experiment	Rate and distribution of groundwater inflow to the array of six 100 m long boreholes	Comparison with predictions by equivalent porous media and fracture flow models
"Second" simulated drift experiment	Rate and distribution of groundwater inflow to the remaining 50 m long D boreholes after construction of the 50 m long Validation Drift	Comparison with predictions by equivalent porous media and fracture flow models, including effects of drift excavation
Fracture distribution in the Validation Drift	Mapping of the fractures in the roof, floor, and walls of the Validation Drift	Comparison with stochastic predictions of fracture patterns by fracture network models
Validation Drift experiment	Rate and distribution of groundwater inflow	Comparison with predictions by equivalent porous media and fracture flow models
"First" radar/saline tracer experiment	Collection of saline tracer in the D boreholes from injections in the H zone, before construction of the Validation Drift	Design of the tracer migration test; calibration of the equivalent porous media and fracture flow transport models
"Second" radar/saline tracer experiment	Collection of saline tracer in the Validation Drift from injections in the H zone	Design of the tracer migration test; comparison with predictions by equivalent porous media and fracture flow transport models; evaluation of effects of drift excavation
Tracer migration experiment	Collection of dye and metal-complex tracers in the Validation Drift and in a borehole from injections in the H zone and the "good" rock	Comparison with predictions by equivalent porous media and fracture flow transport models
Monitoring of groundwater head	Distribution of groundwater heads within and around the SCV site during (i) construction of the Validation Drift, (ii) implementation of the validation experiments, and (iii) draining of the T1 borehole	Comparison with predictions by equivalent porous media and fracture flow models

In Stage IV ("detailed prediction"), the conceptual hydrogeologic model was refined on the basis of data obtained in Stage III. The first radar/saline tracer test was also performed. In this test, a saline tracer was injected into the H zone at a point of intersection with one of the C boreholes, and collected in the D boreholes. Borehole radar tests were conducted during the injection-collection process.

In Stage V ("detailed evaluation"), the Validation Drift was constructed in the region outlined by the first 50 m of the D boreholes and the groundwater inflow rate and distribution were measured. These measurements were compared with modelling predictions made in Stage IV. In addition, a second radar/saline tracer test was performed by injecting a saline tracer into the H zone and collecting the tracer in the Validation Drift. Finally, dye and metal complex tracers were injected into the rock mass at various distances from the Validation Drift, principally in the H zone, and collected within the drift. Predictions of the transport of the saline, dye, and metal complex tracers into the Validation Drift were made and compared with the measurements.

4.4.1 Radar, seismic and hydraulic testing

Based on the existing knowledge of the local geology of the Stripa mine and the core logs from the N and W boreholes, there was reason to believe that significant fracture zones existed within the SCV site. To determine the geometric characteristics of these zones, and to locate any other zones that may have been missed by the boreholes, crosshole radar and seismic tests and single-borehole geophysical tests were conducted in the boreholes in Stage I. The testing was conducted in semi-horizontal planes defined by the three N boreholes and the two W boreholes, and confirmed the existence of a number of major and minor fracture zones. Although these zones dipped steeply, their orientations and thicknesses could not be determined with a high degree of resolution because the testing configuration was restricted to a single horizontal plane. In Stage III, further radar and seismic testing, including single-borehole directional radar testing, expanded the database to the point where the geometric characteristics of the fracture zones could be defined with a relatively high degree of accuracy.

The hydrologic characteristics of the SCV site were evaluated by means of hydraulic packer tests in single boreholes and in the crosshole mode, and by hydraulic head monitoring with the Piezomac system that was installed in existing boreholes in the Stripa mine. The hydraulic tests focussed on the most permeable sections of each borehole, and straddle packers were used to isolate intervals of variable length containing single fractures, when possible. The testing indicated that the bulk of the groundwater flow occurred in a few highly transmissive fractures that represented about 1% of the total number of fractures. Measurements of hydraulic head indicated a pattern of high heads to the northeast of the site, with a decrease in heads to the south and west. In effect, the pattern reflected the likely movement of groundwater draining into the mine excavations. Based on the transient data from both the single-borehole and crosshole hydraulic tests, the fracture system within the

SCV site was found to behave as a well-connected network. The hydraulic flow properties of the B and H zones, located predominantly within the centre of the site, were consistent with spherical to cylindrical flow geometries. The geochemical studies indicated that mixed water was formed within the site by the drawdown of shallow water and the upwelling of deep water as a result of groundwater draining from the D boreholes over relatively long periods of time.

4.4.2 Conceptual model of the SCV site

The conceptual model of the SCV site was based on a binary representation of the rock mass, distinguishing between distinct "fracture zones" and "averagely fractured rock". A "fracture zone index" was developed from a detailed analysis of data from single borehole measurements, including normal resistivity, sonic velocity, hydraulic conductivity, fracture frequency, and the occurrence of single-borehole radar reflectors. The analysis involved the calculation of a matrix of correlation coefficients for the data set, and from this, the eigenvectors for the matrix. Each eigenvector represented a particular weighing of the data so that the eigenvector with the largest eigenvalue was taken to indicate the most intensely fractured part of the rock. The frequency distribution of the fracture zone index exhibited a skewed distribution consisting of two parts, as shown in Figure 4-8. One part is a basically normal distribution centered around a mean value very close to zero,

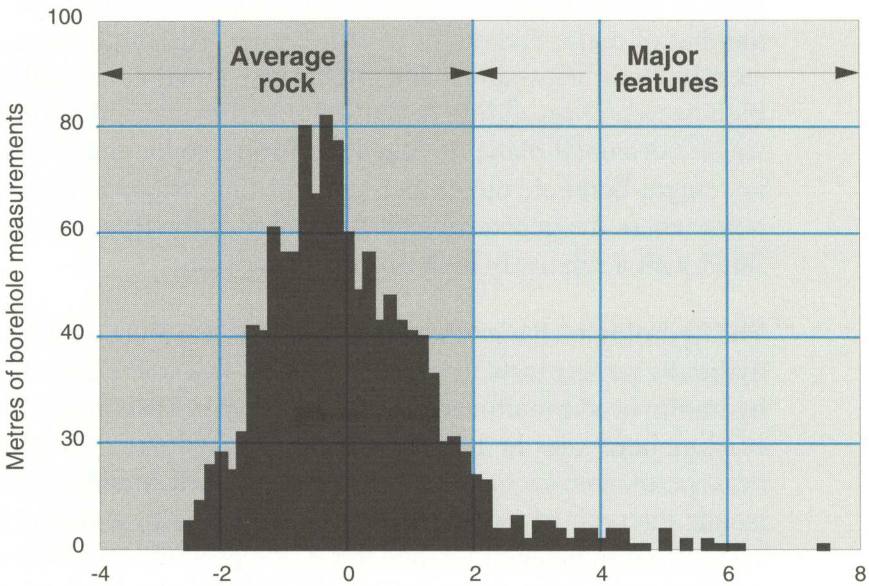


Figure 4-8. Frequency distribution of "fracture zone index" (Olsson, O.J., 1992).

Values from the tail of the distribution (FZI>2) are designated as "fracture zones" while values less than 2 are designated as "average rock".

representing the "averagely fractured rock"; the other part is the tail of values greater than two, representing "fracture zones". These fracture zones occupied about 7% of the total length of boreholes at the SCV site. The geometric and hydraulic details of the fracture zones were determined subsequently by crosshole testing with radar, seismic and hydraulic methods. The geometric model, developed on the basis of the fracture zone index and the remote sensing data, was checked iteratively for consistency with the crosshole hydraulic responses, head monitoring data, groundwater geochemistry and geologic information from the corelogs and drift wall mapping.

As shown in Figure 4-9, the conceptual model of the SCV site contains three major fracture zones (A, B, and H), ranging from 2 to 12 m thick. These features are believed to extend beyond the limits of the SCV site and to connect to the ground surface. This connection between the SCV site and the surface was thought to cause the high groundwater heads observed at the site. These zones accounted for about 75% of the hydraulic transmissivity, as measured by hydraulic tests in single boreholes. In addition, three minor fracture zones (I, K, and M), were identified. Fractures D and V were inferred on the basis of radar and seismic testing, but were not confirmed by subsequent tests and observations. These minor zones, which had extensions of 50 to 100 m and provided hydraulic connections between zones A, B, and H, accounted for approximately 4% of the hydraulic transmissivity measured in the boreholes. Crosshole hydraulic testing confirmed that the conceptual model was consistent with the groundwater flow through the site.

4.4.3 Validation experiments

Prior to the outset of the SCV programme, a decision was made to perform at least two experiments to evaluate the validity of modelling approaches for simulating groundwater flow and solute transport. The first experiment (later named the Validation Drift Experiment) involved measuring groundwater flow into a drift constructed within the SCV site. This experiment was followed by a second experiment (later named the Tracer Migration Experiment), in which tracers were injected into the rock mass surrounding the drift and collected in the drift. During the development of the investigation plans for the SCV programme, it was decided that the first experiment should be preceded by an experiment (known as the Simulated Drift Experiment) that involved measuring the inflow of groundwater to an array of boreholes which outlined the periphery of the Validation Drift in the SCV site. At the time these experiments were planned, the location and size of the SCV site had been identified in a preliminary fashion, but the structural and hydraulic characteristics of the rock mass were, for all practical purposes, unknown. The orientation and dimensions of the Validation Drift would be selected after the preliminary characterization of the SCV site had been completed in Stage I of the programme. In addition, the details of the experiments could be developed only after this characterization information became available.

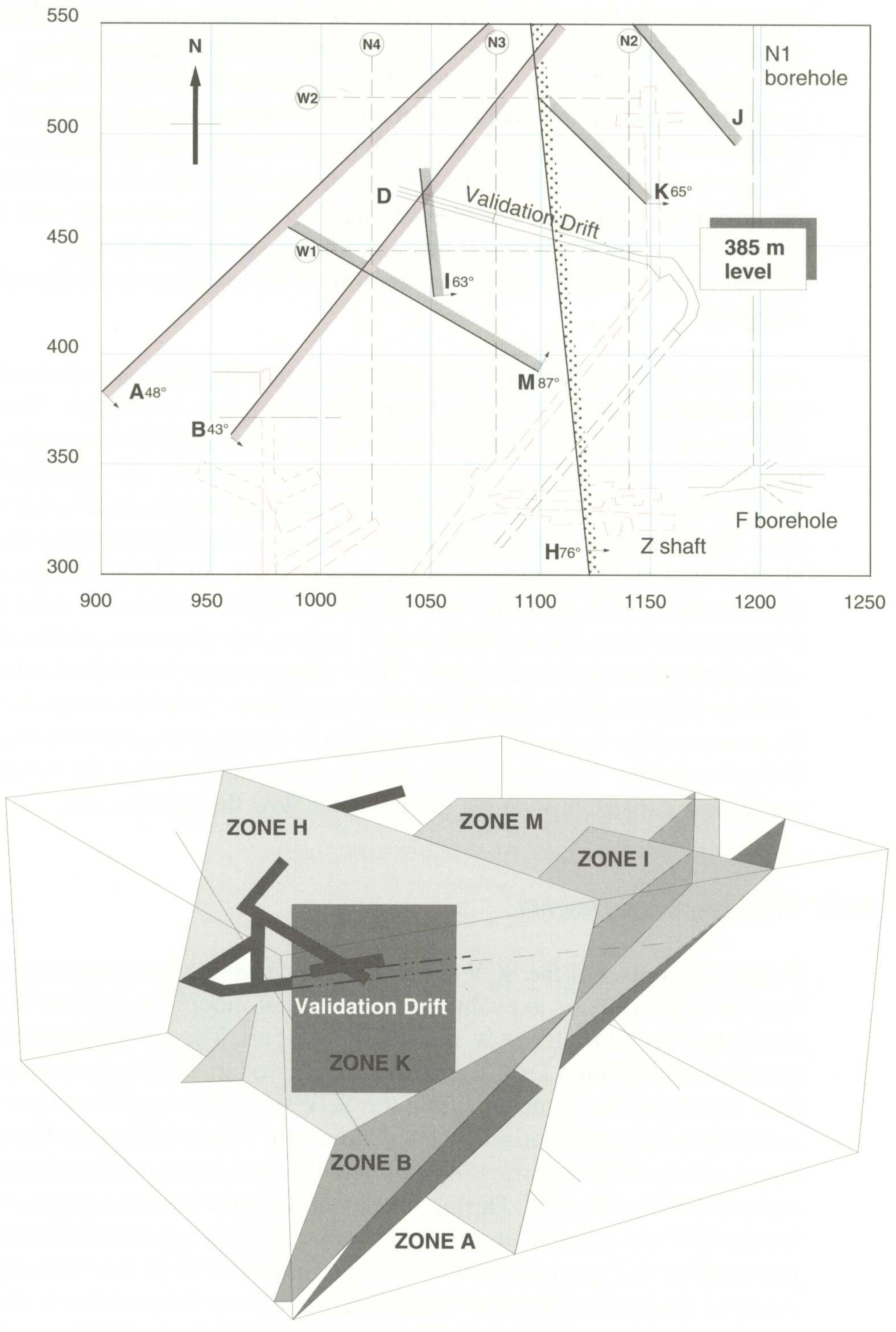


Figure 4-9. Plan and perspective views of the conceptual model of the geologic structure at the SCV site (Olsson, O.J., 1992).

The list of experiments performed at the SCV site is shown in Table 4-2. In addition to the three experiments described above, five experiments were conducted during the various stages of the SCV programme to evaluate the validity of certain aspects of the modelling approaches, design the tracer migration experiment, and assess the influence of the disturbed zone around the Validation Drift on groundwater flow and solute transport. Groundwater flow to the remaining sections of the D boreholes was measured in the second simulated drift experiment, after construction of the Validation Drift. The measurement was intended to quantify precisely the inflow, mainly from the "averagely fractured rock", together with any disturbance induced by the Validation Drift. The fractures in the roof, floor and walls of the Validation Drift were carefully mapped for comparison with stochastic predictions of the patterns of such fractures by the fracture-network components of the groundwater flow and transport models. The groundwater heads within and around the SCV site were monitored continuously during the characterization, construction and experimental activities. These data were used for developing the numerical models of the hydrogeology of the site, and for comparison with the hydraulic heads predicted by the models.

Two radar/saline tracer experiments were conducted to evaluate the validity of solute transport models, provide input to the design of the subsequent tracer migration experiment, and evaluate the influence of the disturbed zone around the Validation Drift. The radar tomograms depicted the migration of tracers within the H zone before and after construction of the Validation Drift. The comparison of the saline tracer collected in the D boreholes before excavation with the saline tracer collected in the Validation Drift after excavation is shown in Figure 4-10. The disturbance created by the drift reduced the recovery of tracer to less than half of that recovered in the D boreholes,

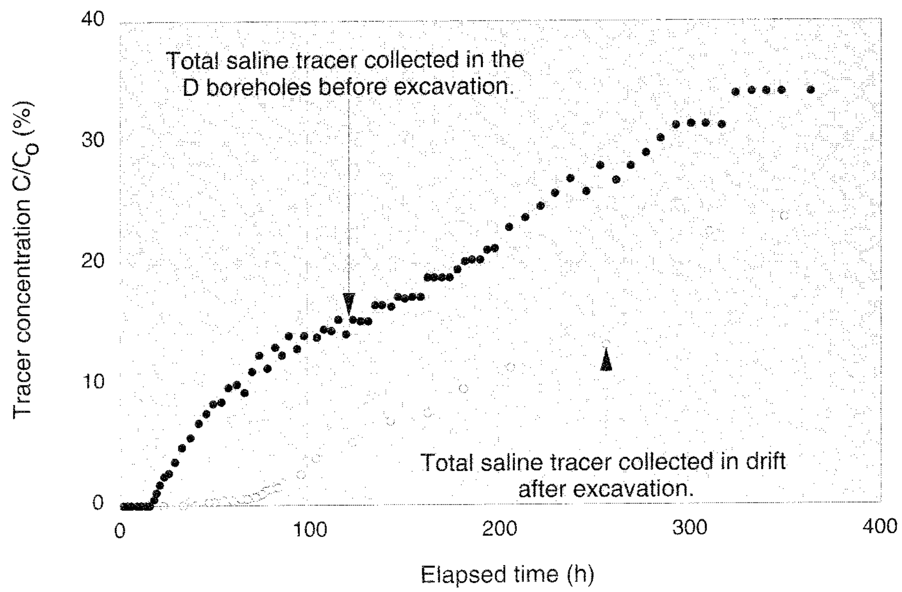


Figure 4-10. Comparison of the total saline-tracer collection before and after excavation of the Validation Drift at the SCV site (Olsson, O.J., 1992).

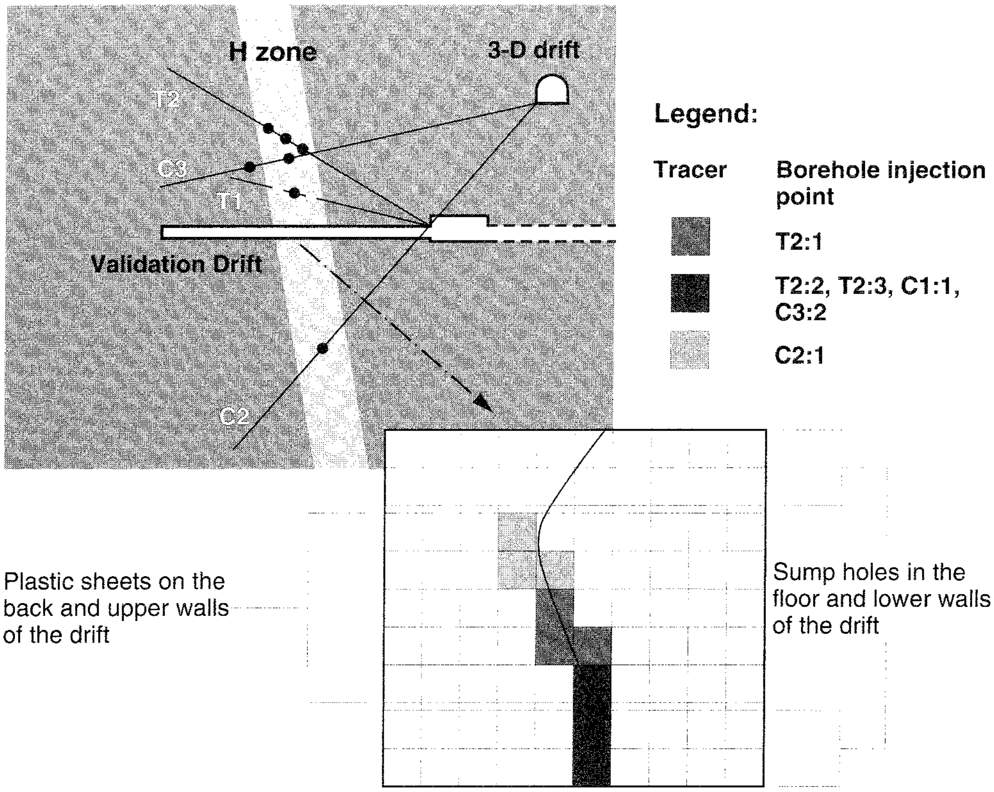
and increased the breakthrough time by many hours. Additionally, the total rate of groundwater flow into the drift was only about 10–15% of that collected in the first 50 m of the D boreholes before excavation. The radar tomograms indicated a significant redirection of tracer migration from the H zone in the vicinity of the Validation Drift to adjacent minor fracture zones. In effect, the "sink" effect was stronger in the first experiment than in the second one, even though the source strength was the same in both cases. In contrast, the measured head difference in the second experiment was approximately 340 m, compared to 65 m in the first experiment. Clearly, the disturbed zone significantly reduced the transmissivity of the rock immediately around the drift, thereby altering the magnitudes and directions of the components of the hydraulic conductivity tensor.

As shown in Figure 4-11, the subsequent tracer migration experiment focussed principally on the migration of tracers in the H zone because most of the groundwater inflow into the Validation Drift originated from that fracture zone. The experiment used dyes and metal complexes as tracers. All but one of the injection points were located primarily in the zone above and below the drift. Significant quantities of tracers arrived at the measuring points in the drift within a few hundred hours. Most of the mean residence times for individual tracers, based on fitting the breakthrough curves with an advection-dispersion model, were calculated to range between 1,200 and 5,000 hours (50 to 208 days).

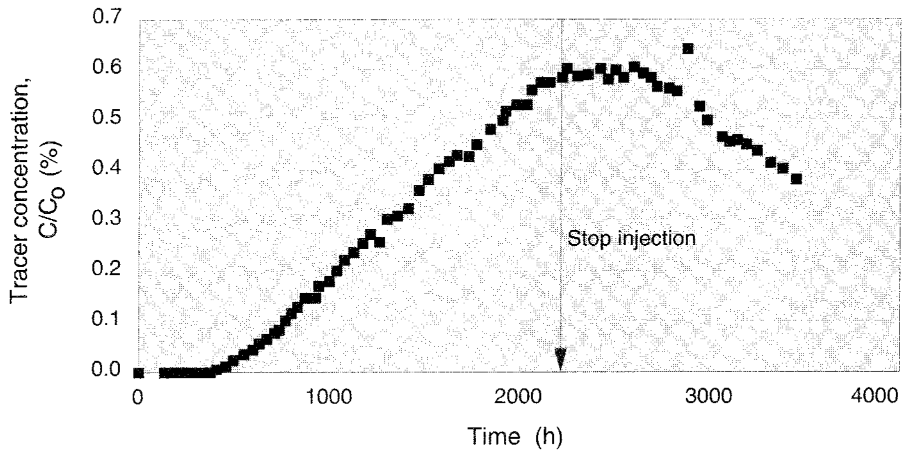
4.5 GROUNDWATER FLOW AND SOLUTE TRANSPORT MODELS

During the last stages of Phase 2 and throughout Phase 3, the characterization tools and methods were applied to develop and refine models of the hydrogeology of the Stripa mine and its surroundings. In particular, hydrogeologic models were developed for the Crosshole site in the vicinity of the 360 m level of the Stripa mine, the general area of the Stripa mine, and the SCV area in the vicinity of the 385 m level of the mine. In addition to providing a basis for the development and application of groundwater flow and transport models, these models were useful in demonstrating the applicability and credibility of the characterization tools and methods.

The principal objective of the SCV programme in Phase 3 was to integrate different tools and methods, in order to 1) predict the groundwater flow and transport in a specific volume of the Stripa granite and 2) compare the predictions against the experimental measurements made at the SCV site. In 1987, the JTC established a Task Force on Fracture Flow Modelling to guide the development of numerical models for groundwater flow and solute transport and to develop criteria to be used for their verification and validation.



Location of major tracer recovery in the Validation Drift.



Breakthrough curve for tracer injected in borehole T2.

Figure 4-11. Schematic layout and typical results from the tracer test in the Validation Drift (Birgersson et al, 1992).

The fracture flow modelling studies were carried out by three independent groups: the Atomic Energy Authority (AEA) Harwell in the United Kingdom, sponsored by the Stripa Project; and the Lawrence Berkeley Laboratory (LBL) and Golder Associates, both in the USA and sponsored by the U.S. Department of Energy (USDOE). In addition, Fracflow Consultants in Canada, sponsored by the Stripa Project, were responsible for development of the equivalent porous media (EPM) models of the Stripa area, the Stripa mine, and the portion of the mine within which the SCV site was located.

4.5.1 Model development

Development of the models began with procedures for the stochastic generation of fracture networks, was followed by modelling of groundwater flow in the SCV site, and concluded by modelling tracer transport by groundwater flow in the SCV site.

The modelling methodology developed by the group at AEA Harwell was able to account explicitly for the fractures identified by the remote sensing tests at the SCV site, as well as to generate stochastically a fracture network for parts of the rock mass at the SCV site where statistical properties of the fracture system were known (Herbert et al, 1991; Herbert and Lanyon, 1992). The AEA Harwell approach is capable of including variability of transmissivity within the fracture planes or, alternatively, of deriving a permeability tensor for the intact rock to be used in a stochastic continuum model.

The methodology developed by Golder Associates involves creation of a semi-stochastic discrete fracture system that combines deterministic information on portions of fracture zones with statistical information on the properties of hydrologically conductive fractures (Dershowitz et al, 1991a, 1991b; Dershowitz and Wallmann, 1992). The fractures in the intact rock are assumed to be distributed randomly, and the fracture area per unit volume of rock is increased for fracture zones identified by geophysical methods. The discrete fracture network model is shown in Figure 4-12.

The approach adopted by LBL focussed on the fracture zones that were identified by geophysical methods, and considered the intact rock to be impermeable (Long and Karasaki, 1992; Long et al, 1992). The fracture zones were discretized into a regular grid. Each grid consisted of a combination of equally conductive channels (i.e. grid spaces) and "blocked" or non-conductive channels, in order to provide an equivalent representation of heterogeneity. The fractures within the zones were represented as a partially filled lattice of one-dimensional conductors, where the degree of filling in a fracture was selected by comparing the predicted flow in the fracture against the actual hydrological data.

The simulation of groundwater flow and transport at Stripa by the EPM modelling approach, adopted by Fracflow Consultants, used the established

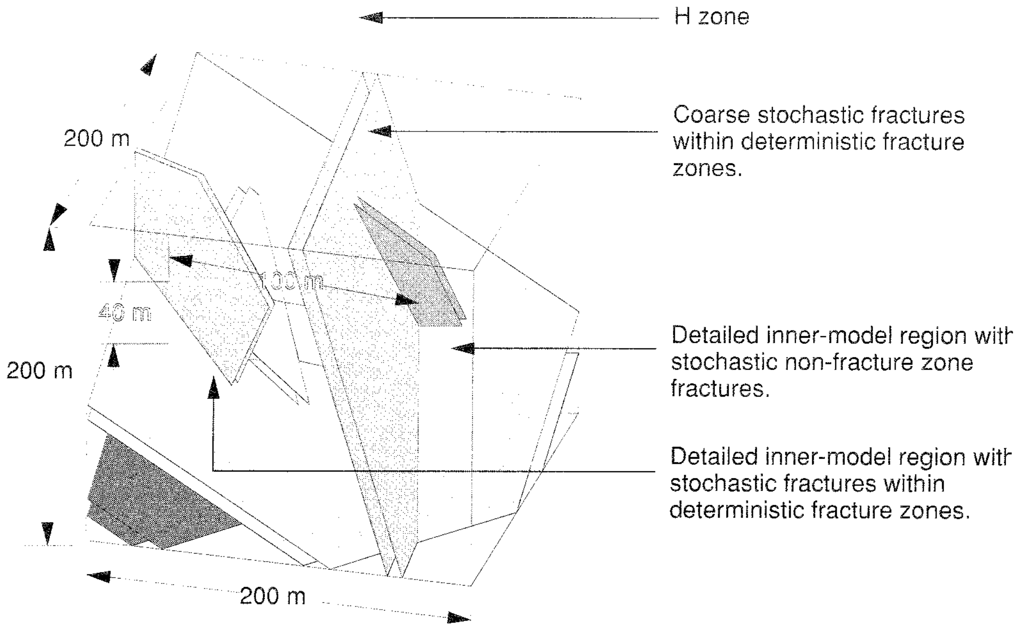


Figure 4-12. Discrete fracture network model of the SCV site (Dershowitz et al, 1991).

This discrete fracture network model, developed by the Golder Associates modelling group, encompasses the entire SCV site.

CFEST (Coupled Flow, Energy and Solute Transport) code (Herbert et al, 1991; MacLeod et al, 1992).

4.5.2 Model validation process

The Task Force on Fracture Flow Modelling established, first, an exercise for cross- verification of the various modelling approaches for groundwater flow and transport; and, second, a process for evaluating the validity of the models (Gnirk, 1992). This process (illustrated in Figure 4-13) involved the task force, the principal investigators, the TSG and the JTC.

4.5.3 Model validation criteria

Recognizing that both definitions and requirements for model validation varied from country to country and that the issue was still being discussed at the international level, the task force decided to adopt an operational definition of validation for the SCV programme. Thus, a model would be considered to be validated for use in a given application when the model had been determined, by appropriate measures, to provide a representation of the process or system that was acceptable to an assembled group of knowledgeable experts.

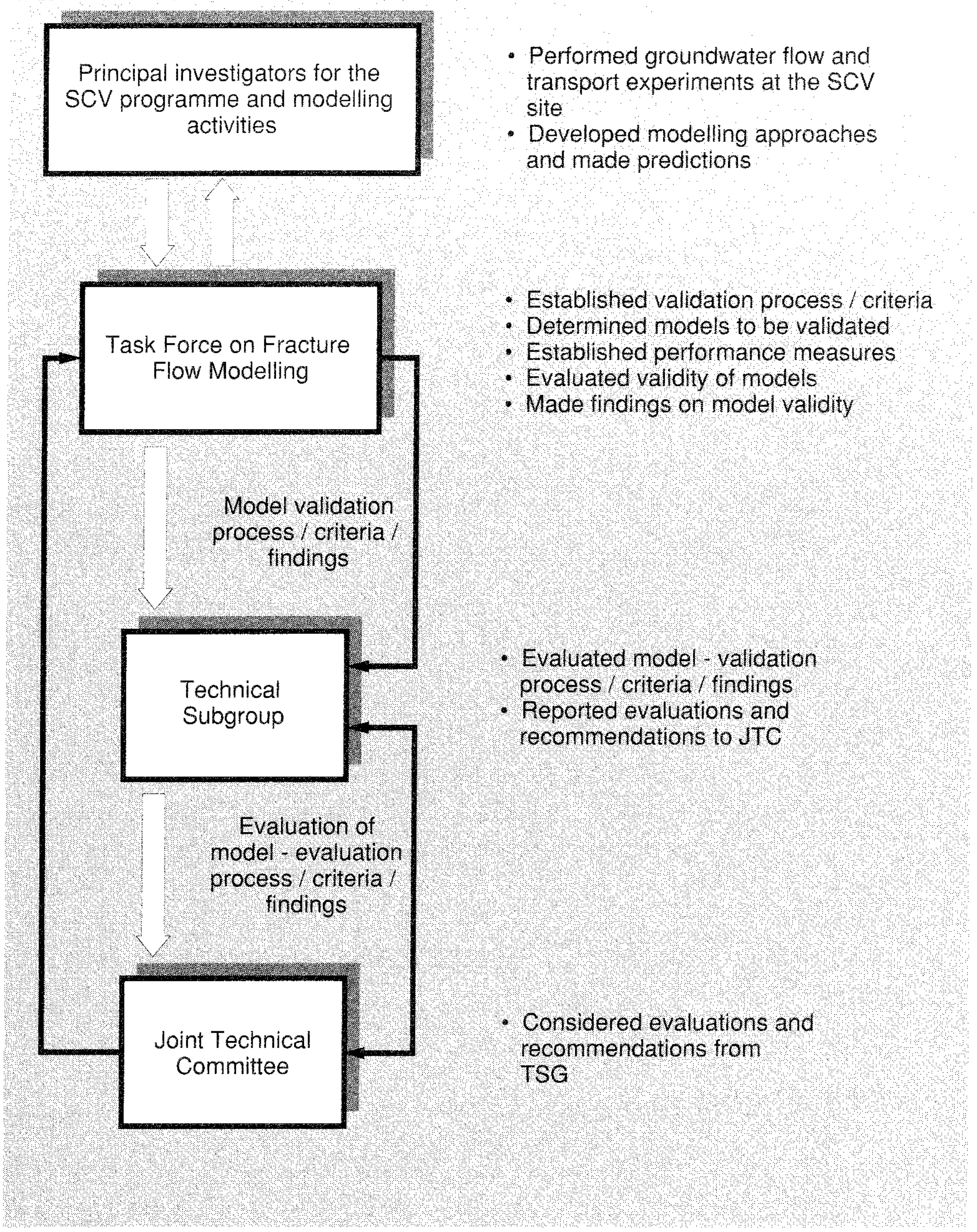


Figure 4-13. Process for evaluating the validity of the groundwater flow and transport models at the SCV site (Gnirk, 1992).

In terms of the given application in the Stripa Project, the task force decided that judgments of model validity would be made only in the restricted sense of simulation of groundwater flow and solute transport in the saturated granitic rock mass in the SCV site. The "appropriate measures" were defined to mean a comparison of model calculations against field observations and/or data from experimental measurements, considering the extent and nature of uncertainties in calculations, observations and measurements in relation to those allowable for purposes of the application. By decision of the JTC the members of the Task Force on Fracture Flow Modelling comprised the "group of knowledgeable experts".

With respect to the performance measures for the various validation exercises, the task force established two sets of criteria for evaluating the validity of a modelling approach and the validity of the components of the modelling approach. These criteria were stated as two sets of questions.

The first set addressed both quantitative and qualitative features.

- *Quantitative*: do the predictive calculations adequately reflect the measured values? That is, are the predictions of the correct order of magnitude as compared to the measurements?
- *Qualitative*: for the purposes of this application, are the predicted distribution patterns sufficiently accurate as compared to the observations? That is, are the predictions of the patterns reasonable when compared to the observations?

The second set addressed the usefulness and feasibility of a modelling approach from the larger viewpoint of general applicability.

- *Usefulness*: is the modelling approach useful for representing groundwater flow and transport in a hydrogeologic environment similar to that of the SCV site?
- *Feasibility*: can the data required to support fully the modelling approach be collected in a feasible and timely manner?

Evaluation of the validity of the groundwater flow and transport models involved two steps: 1) a "training exercise" and 2) a "validation exercise". In each exercise, the modellers were asked to predict the results of the validation experiments conducted at the SCV site without prior knowledge of the outcomes.

4.5.4 Groundwater flow models

The training exercise for the groundwater flow models involved predicting the total rate of groundwater flow into the D boreholes at the SCV site, and predicting the distribution of groundwater inflow along the D boreholes (Hodgkinson, 1991). The modellers were allowed to use the preliminary hydrogeologic model that had been developed on the basis of data gathered in Stage I of the SCV programme. The measurements at the SCV site yielded a water inflow to the boreholes in the range of 1.67 to 1.75 l/min, with the bulk of the inflow originating from the H zone and the three other major fracture zones (Figure 4-9). The three fracture-flow modelling approaches predicted mean inflows of 1.45 l/min (Harwell/Fracflow); 1.5 l/min (Golder); and 3.1 l/min (LBL), all of which are close to the measured inflow. In addition, the models predicted that the bulk of the inflow would originate from the major fracture zones. The agreement between predictions and measurements, from both the quantitative and qualitative viewpoints, was remarkably good, and provided confidence that some acceptable level of success could be achieved in the validation of the models.

In step 2, the validation exercise involved predicting: (i) the total rate and distribution of groundwater inflow to the Validation Drift; (ii) the rates of groundwater flow into the drift from the significant fracture zones; and (iii) the response of the groundwater head distribution in the SCV site to construction of the drift (Hodgkinson and Cooper, 1992a). In addition, the modellers were asked to predict (iv) the fracture patterns that would be observed in the walls of the drift, and (v) the distribution of groundwater flow into the remaining sections of the D boreholes that were located beyond the end of the drift. The modellers were allowed to use the conceptual hydrogeologic model of the SCV site that included the refinements and additional detail provided by the test data collected during Stage III of the SCV programme. Finally, the modellers had to consider the effect of stress redistribution, caused by drift construction, on the hydrologic properties of the rock mass.

Based on measurements in the Validation Drift, the groundwater inflow was considerably less, by a factor of about 8, than was expected on the basis of the inflow into the D boreholes (Olsson, 1992). Approximately 97% of the inflow originated from the H zone. Although the values of predicted groundwater inflows to the Validation Drift varied considerably from those measured, the mean values were all within a factor of 2 to 7 of the measured inflow (see Figure 4-14) . The influence of stress redistribution in the rock mass because of drift construction was treated differently by the various modellers. In the EPM model used by Fracflow Consultants and in the fracture flow model used by AEA Harwell, the fracture transmissivities were modified according to the calculated change in the state of stress and a laboratory-derived relationship between transmissivity and normal stress. The fracture flow models used by Golder Associates and LBL incorporated a skin factor, based on empirical evidence, wherein the transmissivity of the rock mass within 3 to 5 m of the drift wall was reduced by about an order of magnitude.

The predictions of both the fracture patterns in the Validation Drift and the magnitude and spatial distribution of head changes in the SCV site due to excavation of the drift were reasonably good, considering the stochastic nature of the fracture networks. The principal difference between the three fracture flow modelling approaches consisted of the assumed density of fractures in the rock mass between the discrete fracture zones. AEA Harwell and Fracflow Consultants employed fracture statistics to define a network model that was used to determine the permeability of an equivalent homogeneous medium, which in turn provided the boundary conditions for more detailed models of inflow. The fracture flow model of Golder Associates included the fractures explicitly, focussing on the most transmissive fractures, with inferred fracture frequencies in the H zone and in the intact rock near the drift, and no fractures in the intact rock situated away from the drift. The LBL group modelled flow in the fracture zones only, and assumed the intact rock to be impermeable.

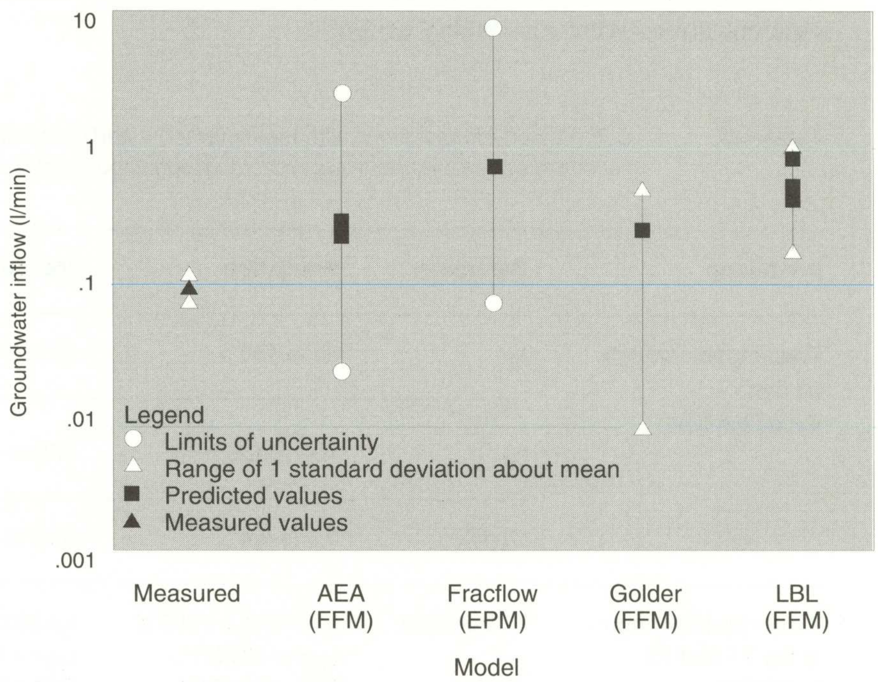


Figure 4-14. Comparison of the measurements with the model predictions for groundwater inflow into the Validation Drift (Hodgkinson and Cooper, 1992a).

FFM designates fracture-flow model and EPM designates equivalent porous media model.

Considering only the effect of stress redistribution on the transmissivity of the rock mass in and around the Validation Drift, none of the modelling groups was able to explain the substantial decrease in groundwater flow into the drift. However, as the radar tomograms from the saline tracer experiments demonstrated, the disturbed zone caused a significant redirection of groundwater flow away from the drift. This suggested that the hydraulic conductivity of the rock in the immediate vicinity of the drift had been reduced, perhaps substantially.

4.5.5 Solute transport models

In order to evaluate the validity of transport models, the training exercise in step 1 involved predicting the results of the second radar/saline tracer test (Hodgkinson and Cooper, 1992b). In this test, the saline tracer was collected in both the SCV drift and boreholes in the H zone. The modellers were asked to predict the saline breakthrough curves and to develop histograms of the breakthrough concentrations in the D boreholes. They were allowed to use the refined hydrogeologic model of the SCV site, the groundwater flow measurements into the Validation Drift and the results of the first radar/saline experiment. Table 4-3 compares the measurements with the predictions produced by the Golder fracture flow model. The saline breakthrough times and concentrations were well within an order of magnitude of those measured, and the predicted locations of measurable breakthrough concentrations were reasonably accurate.

Table 4-3. Comparison of predictions with measurements and observations for the second radar/saline tracer experiment[1] (Hodgkinson and Cooper, 1992b).

Prediction	Parameter	Prediction	Measurement
Tracer breakthrough to the Validation Drift	t_5	30 to 150 h	60 to 70 h
	t_{50}	100 to 150 h	125 to 150 h
	C_{ss}/C_o	0.3 to 0.4	0.36 to 0.40
Tracer breakthrough to the T1 and T2 boreholes	T1 borehole	t_5=100 to > 1000 h t_{50}= > 1000 h C/C_o=0 to 0.03	t_5=200 h t_{50}= > 600 h C/C_o=0.07
	T2 borehole	t_5=100 to > 1000 h t_{50}= > 1000 h C/C_o=0 to 0.03	t_5=450 h t_{50}= > 1000 h C/C_o=0.01
Tracer breakthrough to the grid elements in the Validation Drift		t_5=20 to 550 h where measurable t_{50}=200 to 500 h where measurable C/C_o=0.01 to 1 where measurable	t_5=50 to 500 h t_{50}=96 to 800 h C/C_o=0.13 to 0.84

[1] See Figure 4-11 for location and outline of experiment. See Figure 4-15 for meaning of t_5, t_{50} and C_{ss}/C_o.

Step 2 of the effort to evaluate the validity of the transport models involved predicting the outcome of the tracer test in the Validation Drift (Hodgkinson and Cooper, 1992b). As discussed in Section 4.4.3, this test involved injecting a variety of dyes and metal complexes, principally in boreholes that intersected the H zone, and collecting the tracers in the Validation Drift. The modellers were asked to predict the tracer concentrations and arrival times in the Validation Drift and the boreholes, and the pattern of distribution of tracer arrivals in the drift. As shown in Figure 4-15, the predictions of tracer concentration agreed reasonably well with the measurements. However, the models tended to underestimate the time required for the tracers to travel from the injection points in the H zone to the collection points in the Validation Drift.

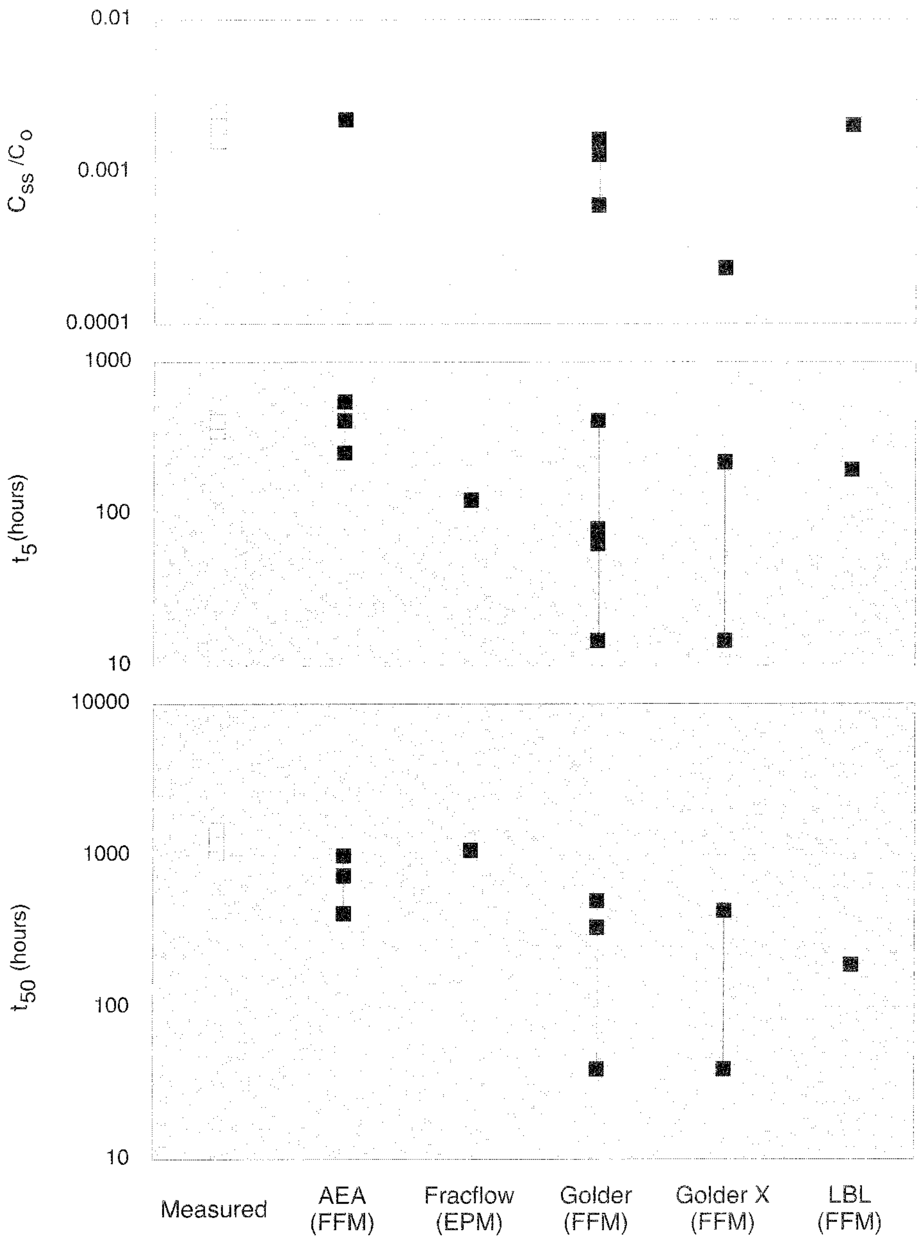


Figure 4-15. A comparison of observed and predicted breakthrough curves for tracer injection in the first interval of borehole C2 and recovery in the Validation Drift (Hodgkinson and Cooper, 1992b).

C_{ss}/C_o is the ratio of the "steady-state" tracer concentration measured in the drift to that injected into the borehole interval. t_5 and t_{50} are the times at which 5% and 50%, respectively, of steady-state breakthrough were observed. FFM signifies fracture flow model and EPM signifies equivalent porous media model. The vertical lines between the solid squares represent the ranges of predictions.

4.5.6 Assessment of model validity at the SCV site

At the close of the SCV programme, the task force made consensus judgments on the validity of the various modelling approaches in simulating groundwater flow and transport at the SCV site (Hodgkinson, 1992; Hodgkinson and Cooper, 1992a, 1992b). All of the modelling approaches were judged to be capable of making predictions that were the correct order of magnitude as compared to the experimental measurements. It must be noted, however, that the influence of the disturbed zone on groundwater inflow to the Validation Drift could not be totally explained by the manner in which the effects of stress redistribution were treated. Furthermore, the transport models tended to underestimate the time required for a tracer to migrate from the point of injection to the point of recovery. This discrepancy may have been due to the choice of the value for dispersivity.

The task force framed its judgments of model validity against the qualitative criterion (see 4.5.3) in reference to the near field (within several excavation diameters of the drift wall) and the far field (beyond several excavation diameters). The fracture-flow modelling approach used by Golder Associates was judged to yield reasonable patterns of phenomena in both the near field and far field. A similar judgment was made for the combined application of the fracture-flow modelling approach by AEA Harwell and the EPM modelling approach by Fracflow Consultants. The very detailed stochastic modelling of the fracture network in the AEA Harwell approach yields good results in the near field, but is somewhat impractical for a large rock mass because it requires a computer with a very large storage capacity. On the other hand, the EPM model gives good results in the far field, but requires a high degree of discretization of the finite element mesh in order to achieve good results in the near field. The modelling approach chosen by LBL considered groundwater flow and solute transport through deterministic fracture zones, and assumed that the rock mass between fracture zones was impermeable. As a consequence, there was no basis on which to judge whether the model could produce reasonable patterns of phenomena in the near field. Furthermore, the number of realizations for the experiments was insufficient to demonstrate that the approach was capable of producing consistent patterns. However, the task force felt that the modelling approach had potential, perhaps more as a research tool than as an applied technique.

The task force concluded that the fracture-flow modelling approach by Golder Associates, and the combination of approaches used by AEA Harwell and Fracflow Consultants for fracture-flow and EPM modelling, respectively, were useful for simulating groundwater flow and solute transport in a hydrogeologic environment similar to the environment at the SCV site. Because the number of realizations was not sufficient to fully demonstrate the usefulness of the LBL modelling approach at the SCV site, the task force could only judge the approach to be potentially useful. The consensus judgment of the task force was that the necessary data could be collected in a feasible and timely manner to support each of the four modelling approaches. This fact was clearly demonstrated over the five years of the SCV programme. It must be kept in mind, however, that the data required to support the modelling approach by LBL are principally the product of hydraulic head testing in a groundwater system, whereas the data required to support the other three modelling approaches are derived from fracture mapping and hydraulic packer tests.

4.6 SIGNIFICANT ACHIEVEMENTS

Over a period of some thirteen years, the investigations of methods and techniques to characterize the natural barriers evolved through successive stages of learning, development and application. This evolution of activities involved the collective thinking and efforts of the group of scientists and engineers from seven to nine countries who were responsible for the planning, review, investigation and management of the project.

The significant achievements of the project, in terms of their contribution to site characterization in general, were:

- *Demonstration of a programme of progressive site characterization.* The SCV site, which encompassed about 1 million m^3 of rock, was characterized in progressive stages over a period of about five years. Based on remote-sensing data from only five boreholes in the site during the first stage of characterization, it was possible to identify the locations of the principal structural features and hydraulic anomalies. This information provided a basis for deciding upon the orientation and length of boreholes to be drilled to obtain a more detailed characterization of these features and anomalies. The test data from these additional boreholes subsequently provided the basis for determining the dimensions of the Validation Drift that was constructed in the SCV site and for designing the groundwater inflow and tracer tests in the rock mass surrounding the drift. At the outset of the SCV programme, it had already been decided that these tests would be conducted in the last stage of the programme. However, the specific details of the tests could not be determined until the principal structural features and hydraulic anomalies within the site area had been identified and initially characterized.

- *Procedure for developing a conceptual hydrogeologic model.* During the mid-years of the Stripa Project, the principal investigators developed conceptualizations of the hydrogeology of the Stripa area and the Crosshole site in the Stripa mine. The conceptual model of the Crosshole site was developed principally to illustrate the integrated use of core logs, borehole photography, and single-hole and crosshole testing with radar, seismic and hydraulic techniques. The model of the Stripa area was developed principally to complement the characterization work that was beginning at the SCV site, as well as to illustrate how the large collection of geologic, hydrologic, and geochemical data for the general area and the mine could be assembled in a consistent, realistic fashion. During the early stages of the SCV programme, a conceptual model of the hydrogeology of the SCV site was developed on the basis of core logs, drift mappings, borehole test data, and the information provided by the conceptual model of the Stripa area. In the later stages of the programme, as more data was obtained from additional boreholes, the conceptualization of the hydrogeologic characteristics of the site was refined. Through these efforts, a procedure for the rational and consistent development of a conceptual hydrogeologic model of the Stripa rock mass evolved. The procedure incorporated testing techniques and methods, consistency checks and decision points concerning the need for more data. Although the intended use of a conceptual model will differ from site to site, as will the amount of data required for details and consistency checks, this procedure serves as an example of a rational and systematic development process.

- *Demonstration of a process for evaluating the validity of numerical models.* An evaluation of the validity of models of groundwater flow and solute transport was an integral part of the SCV programme. To this end, the JTC established the Task Force on Fracture Flow Modelling, consisting of recognized experts from the member countries. The task force, in concert with the principal investigators, developed a formal process for evaluating the validity of the models that were applied at the SCV site. The process involved defining the appropriate measures for the evaluation, including the scope of the evaluation, and the criteria against which the validity of the various models and modelling approaches could be judged by a group of knowledgable experts. The process required close cooperation and coordination among the experimenters, the modelers, and the experts. At the close of the SCV programme, the experts made documented judgments of the validity of various approaches for modelling groundwater flow and transport in the SCV site. This effort constitutes a case-history example of a formalized and deliberate approach to evaluating the validity of numerical models for a very specific application.

From the particular viewpoint of a saturated, fractured granitic rock mass, the significant achievements of the project were:

- *Development of a suite of tools for hydrogeologic characterization.* These tools included the radar, seismic and hydraulic methods for both single-borehole and crosshole testing, as well as borehole photography and drill-core observations. For site conditions similar to those encountered at Stripa, including groundwater with a low salinity, tests in boreholes spaced as much as 200 m apart can be expected to produce data to identify the principal structural features and hydraulic anomalies. The hydraulic conductivities of the rock mass in the SCV site ranged from 10^{-7} m/s for the fracture zones to as low as 10^{-11} m/s for the "competent" rock.

- *Development of methods and techniques for geochemical characterization.* This work involved the development and implementation of methods and techniques to determine the history, or residence time, and origin of groundwater in the granitic rock mass at Stripa, including water sampling techniques and identification of concentrations of key radionuclides.

- *Demonstration of the applicability of the equivalent porous media (EPM) approach for simulating groundwater flow and transport.* The

EPM modelling approach was used to simulate groundwater flow and transport in hydrogeologic models of the Stripa area, the Stripa mine and a portion of the mine containing the SCV site. These models represented volumes of rock ranging from about $300 \cdot 10^9$ m^3 to some $5 \cdot 10^6$ m^3. The calculations of groundwater inflow to the mine agreed quite well with the measured pumping rate when the models for the Stripa area and the Stripa mine were used. This agreement is a significant achievement, considering the sizes of the areas modelled and the relative sparseness of the geologic information and hydraulic data. The predictions of groundwater flow and transport within the SCV site for the validation experiments also were reasonably good, considering the relatively coarse discretization of the rock mass as compared to the dimensions of the Validation Drift.

- *Demonstration of the applicability of the fracture flow modelling for simulating groundwater flow and solute transport.* Three fracture flow modelling approaches were used with reasonable success to simulate groundwater flow and transport within the SCV site. The approaches differed in the manner in which the fracture networks were constructed, in the exent of the regions modelled within the site, and in the types of input data required from the characterization activities. The combination of approaches and the differences among them provided a rather robust demonstration of modelling capability and usefulness.

- *Specification of requirements for design of a tracer test to identify groundwater flow paths.* The tracer tests at Stripa demonstrated the importance of understanding the groundwater flow field and potential pathways in a rock mass prior to conducting a tracer test. There is little hope of quantifying the migration characteristics of a pathway unless the geometries of the pathway and the generalized groundwater flow field within the pathway are defined before tracers are injected into the pathway. This information can be obtained through the integrated use of radar, seismic and hydraulic borehole testing methods. In addition, the sorbing characteristics of the tracer substance must be determined *a priori* in the laboratory.

- *Demonstration of the influence of the "disturbed" zone around an underground drift on groundwater inflow.* The groundwater inflow to the Validation Drift at the SCV site was almost an order of magnitude smaller than that measured previously in the D boreholes, which outlined the drift periphery before excavation. The radar tomograms from the saline tracer tests indicated qualitatively a substantial redirection of groundwater flow in the H zone around the drift after it was constructed. However, the circumstances that caused the reduced inflow could not be explained quantitatively, even when the redistribution of the stress field, gas bubbles in the water, desaturation of the wall rock, etc., were considered. This unexplained effect was also observed at the site of the 3-D migration drift in the Phase 2 investigations.

5 ENGINEERED BARRIERS

5.1 INTRODUCTION

The construction and operation activities undertaken for a repository for heat-generating radioactive waste will provide, with time, increasingly detailed information on the performance characteristics of the engineered host rock. Features and phenomena that may be important to the performance of the repository or the safety of its operation will be uncovered. It is likely that the repository design will need to be modified in response to these findings. Moreover, engineering measures are generally planned to ensure repository performance. Although this iterative and flexible approach is commonly required in many of the engineering disciplines, it is so important to geotechnical works that it has been formalized by the term "the observational method" (Peck, 1969). This method not only recognizes the need to observe important aspects of the rock mass and its response during construction, but also demands that engineering measures be available prior to construction to counter any reasonably foreseeable performance or safety concern. The engineered barrier studies for the Stripa Project were undertaken to provide a series of technologies that could be applied to these construction and development activities. As may be expected from an appreciation of the "observational method" the engineered barrier studies evolved throughout the programme to reflect the increasing understanding of the Stripa granite. Changing interests of the member countries as national programmes matured also influenced the Stripa work.

A wide range of materials is available for consideration for use in the construction of engineered barriers. Screening studies indicated that clay and cement-based materials were appropriate for study in the Stripa Project. Phases 1 and 2 (1981–1988) of the project focussed on the *in situ* application of swelling, bentonite-clay materials. Bentonite and cement-based grouts were studied in Phase 3 (1991–1992). For both clays and cements, the following issues were considered important to the isolation of heat-generating radioactive waste and addressed throughout the Stripa investigations: measurement of performance; application methods, including aspects of quality control; and material longevity. Specifically, *in situ* experiments yielded information related to 1) the application of laboratory-derived performance data to full-scale repository system performance and 2) the limits to which the engineering processes were effective in the Stripa granite. Laboratory, desk and modelling studies were the primary tools used to evaluate longevity.

To reflect the international interests of the programme, the studies were structured to give, as far as possible, generally applicable results.

During the evolution of the scientific investigation programme at Stripa, and concurrent with other international developments, a better understanding has developed of the natural barriers and of the interactions and necessary integration between natural and engineered barriers. The assessment of integration aspects has progressed from the near field to the far field. Thus, in Phase 1, the emphasis was on engineered barriers in the disposal holes and in the thermally affected zone of the repository; in Phase 2, investigations were aimed at plugging of repository openings such as boreholes, shafts and tunnels; and in Phase 3, considering the progress made in understanding the hydraulic features of the surrounding rock mass, as affected by the engineering processes, the emphasis shifted to sealing of natural and induced fractures in the rock.

This chapter describes and analyses the important aspects of the engineered barriers studies, and summarises many positive results of the programme. These achievements were obtained by adjusting the programme in response to both expected and unexpected results. The adequacy with which issues could be addressed was constrained by costs and other administrative concerns. Balance was sought between the interests of the member countries and the principal investigators. The effects of important, unexpected technical results and administrative factors are discussed in volumes II and III of this overview.

5.2 PHASE 1 – THE BUFFER MASS TEST

In Phase 1, the Buffer Mass Test (BMT) was carried out to examine phenomena and processes related to plugging with clays the excavations near the heat-generating waste containers. The following aspects of repository design, construction and performance were examined:

- engineering feasibility of a specific concept for waste emplacement and plugging of disposal holes;
- materials behaviour; and
- qualification of performance models for hydro-thermo-mechanical interactions between HLW, plugging materials and surrounding rock.

The observations performed in the BMT were expected to assist in improving designs, confirming feasibility and improving understanding of ongoing processes.

Figure 5-1 presents the general layout of the BMT, which was carried out in the Swedish-American Cooperative programme (SAC) macropermeability room. The important information that the SAC investigations provided on the hydraulic properties of the rock mass close to the room could be used both in the design of the experiment and in the interpretation of the test data.

An important objective of the BMT was to investigate the transient processes of heat and water transfer in a highly compacted bentonite-based buffer and the effects of these processes on hydro-mechanical interactions between the

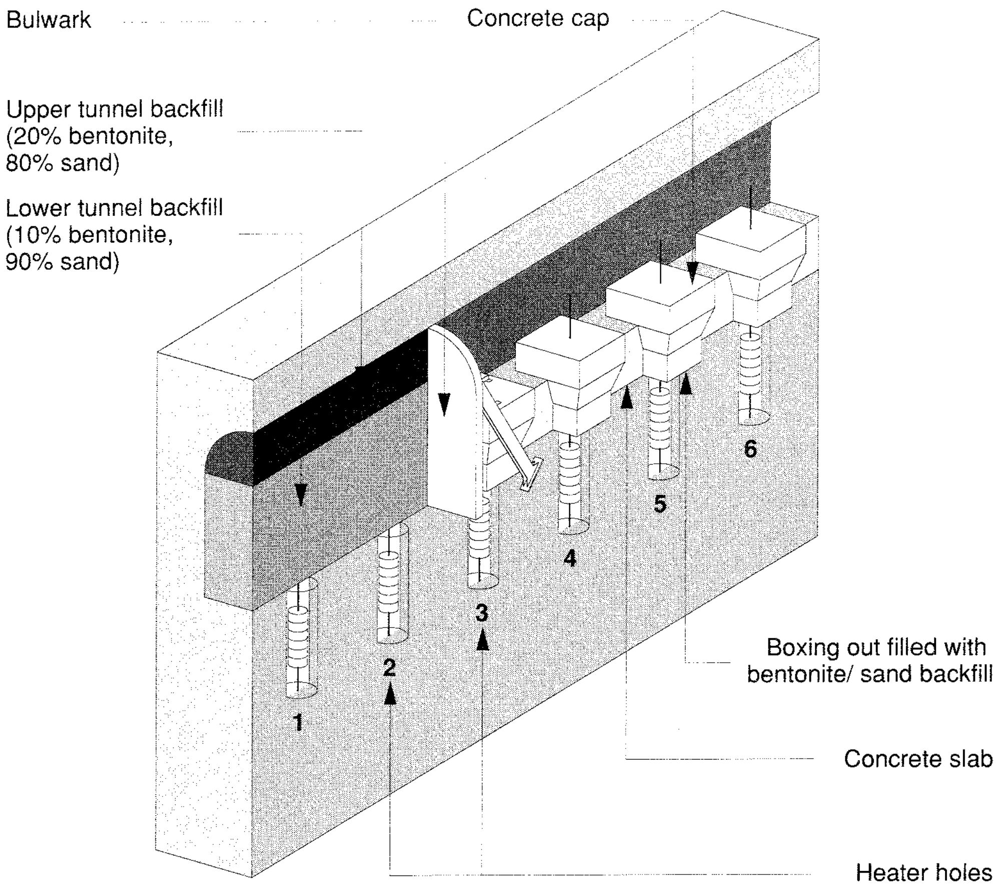


Figure 5-1. The layout of the Buffer Mass Test.

Six 160 mm diameter holes were drilled in line in the floor of the room. The holes were equipped with electrical heaters surrounded by highly compacted bentonite and overpacked with sand-bentonite mixtures. Temperatures, pressures and displacements were monitored over 4 years (Pusch et al, 1985a, 1985b).

rock and the buffer, immediately following waste emplacement in a repository. Given the short duration of the test, it was not possible to examine the radionuclide transport properties of the buffer, other than by implication.

The highly compacted bentonite (HCB) used as buffer in the BMT was prepared by statically compacting MX-80 bentonite to a dry density of at least 1.88 Mg/m^3. The sand-bentonite tunnel backfill materials were compacted *in situ* to minimum dry clay densities of approximately 0.43 (lower backfill) and 0.37 Mg/m^3 (upper backfill). At these densities the buffer probably behaves, when intact, as an almost perfect semipermeable membrane; the backfill materials have lower densities and show lower osmotic potential.

Calculations using numerical models based on Fourier's law for heat transfer in the backfill/buffer/rock system indicated that the test needed to be run for approximately three months to allow for observations on the validity of the model. Calculations for moisture transfer in the system, using numerical models based on isothermal moisture diffusion equations, indicated that the experiment needed to be operated for one or more years.

Uncertainties were evident in the modelling exercises. These related principally to a lack of available data for the transfer parameters employed in the field equations describing heat and moisture transfer. Experience indicated that it was likely that the uncertainties were more significant in the predictions of water transfer than in predictions of heat transfer.

During water uptake, the buffer and backfill materials were expected to swell and develop swelling pressures acting against the other components of the test system. The buffer was expected to exert high ultimate pressures of 10 MPa or more against the rock and the backfills. Pressures of hundreds of kPa were expected from the backfill materials. Interactions would result in deformations of decimetres at the buffer/backfill boundary. Moreover, the swelling pressures could result in clay being extruded into open rock fractures that intersected the excavations in which the experiment was to be carried out.

These hydro-mechanical interactions, because of their largely unknown effects on the hydraulic boundary conditions acting at the buffer/backfill/rock interfaces, further decreased confidence in an ability to predict numerically heater/buffer/backfill/rock performance and interactions with precision. The observations to be made in the BMT were needed to qualify and refine the conceptual models for performance and to provide an indication of the extent to which enhanced numerical prediction capabilities were required or, indeed, possible.

The work for the macropermeability experiment carried out under the SAC agreement, along with observations made in the large-diameter boreholes (Ø = 760 mm, 3 m deep) that were diamond-drilled for the BMT, provided information used to bound the initial hydraulic conditions around the BMT room. Excavating the room at right angles to the horizontal major principal stress resulted in an excavation disturbed zone with a radial hydraulic conductivity that was less than the value of 10^{-10} to 10^{-11} m/s estimated for the surrounding rock mass. Measurable water flows occurred principally in the fractures in the rock mass, although there was evidence of flow in permeable "fracture-free" rock. Only a small fraction of the observed fractures visibly carried water. A large number of the natural fractures were infilled with minerals or otherwise blocked to the transmission of water. The eastern wall and the ceiling of the room appeared likely to provide greater access of water to the backfills than the floor, the western wall and the end of the room. Natural water inflow into the emplacement boreholes varied between holes and was higher in holes 1, 2 and 5 than in holes 3, 4 and 6. Most of the water entered the open large-diameter drillholes through discrete fractures which, reflecting the excavation disturbance, were concentrated in the upper third of the hole and sub-parallel to the floor of the room. The water inflow conditions in the wetter holes made it impossible to infill the construction gap between the HCB buffer and the rock wall with powdered bentonite and, thereby, through practicality, conditioned the layout of the experiment.

A large number of instruments was installed in the buffer and backfills to monitor changes in temperature, total pressure, pore water pressure, moisture content and displacement during the progress of the tests. Water pressure and temperature were measured in the near-field rock mass. Hole 5 was selected for extra instrumentation: the swelling forces from buffer and backfills acting on the cap of the hole and the rock displacements arising from the combined effects of temperature changes and the swelling forces were measured.

Commercially available instrumentation was used wherever possible; much of this instrumentation required modification and calibration for the harsh environmental conditions of temperature, pressure and water salinity expected in the test. Special moisture sensors were developed to monitor transients in the clay masses.

The heaters used in the six emplacement holes were specifically designed to facilitate measurements of moisture content in the HCB at a single point in time at the end of the test. During this activity, precise surveys were used to determine the deformation of the buffer/backfill interface.

It is high testimony to the care taken in the design of the heaters and the special measures taken to protect the other instrumentation that none of the heaters failed during the four years over which the BMT was carried out, and that other instrumentation suffered little from malfunction.

The response of the buffer and backfills to heating and to water supplied through the bounding rock mass depended on the original hydraulic boundary conditions, the test configuration and the interactions between the clays and the rock mass. The temperature distribution, final moisture content distributions and swelling pressures developed by the HCB buffer material were largely controlled by the rate at which water was supplied at the rock/buffer interface. The buffer in wet holes 1, 2 and 5 became saturated within the test period; the buffer in dry holes 3, 4 and 6 showed increasing water content from the heater to the buffer/rock interface, with drying having occurred near the heater. Correspondingly, swelling pressures were higher and temperatures were generally lower in the wet holes than in the dry ones.

Under the force of the swelling pressure, HCB was extruded into fractures in the rock, thereby preventing these fractures from acting as local water sources. The buffer, which originally contained construction joints, took up water through a thin layer of sealed rock and sealed itself. In accordance with expectations, this self-sealing was more pronounced in wet holes than in dry ones. Eventually, when the buffer in dry holes becomes saturated, it is expected to self-seal just as effectively.

The results tended to confirm that an isothermal moisture transfer model could be applied to moisture transfer in the backfill materials in which imposed temperature gradients are small. The isothermal model did not account for moisture transfer that occurred in the HCB buffer. The temperature data, swelling pressure results, moisture redistribution data, results from tracer tests, and retrospective analyses all support the hypothesis that an evaporation/condensation cycle was established down the temperature gradient developed in the unsaturated buffer. The conduct of the BMT showed that moisture transfer under temperature gradients can be significant in dense bentonite materials under repository conditions and, depending on repository design, may need to be accommodated in models of the performance of the near field.

The heat conduction model used tended to overestimate the temperatures to be expected in saturated systems – the ultimate condition expected in a repository.

The mechanical performance of the backfill met all expectations by exhibiting more than adequate resistance to the uplift forces from the buffer. The magnitude of heave at the buffer/backfill interface was well predicted by a simple mathematical model. The effects of swelling pressures from the buffer on the rock mass appeared to be within the accuracy of the instruments and could not be measured. However, the floor of the emplacement room exhibited heave, which was principally attributable to increases in the temperature of the rock and in accordance with understanding. The effects of this movement on water flow in the near-field rock mass could not be established.

Pore water pressures in the rock mass within 1 m of the tunnel faces appear to have been controlled by an excavation disturbed zone (EDZ). Adding to the results from the SAC macropermeability experiment, the BMT results indicated that the hydraulic properties of the EDZ were anisotropic: hydraulic conductivity parallel with the tunnel axis appeared higher than radial hydraulic conductivity. The high axial conductivity fed groundwater to the top of the emplacement boreholes and to the bottom of the tunnel backfills. These data provided significant understanding of the near-field rock mass for the design of grouting experiments carried out during Phase 3 of the Stripa Project.

5.3 PHASE 2 – BOREHOLE, SHAFT AND TUNNEL PLUGGING

Siting a repository for heat-generating radioactive waste will require thorough investigation of the rock mass. Despite the significant advances made in geophysical investigation methods through the Stripa Project and other programmes, it remains clear that the site investigation will include penetration of the rock by investigation boreholes. Thus, most preliminary designs for repositories are based on the assumption that investigation boreholes, if left unfilled during repository closure, may act as preferential pathways for radionuclide migration and release. The same concern exists for shafts and tunnels used to develop and access the disposal levels of a repository. Phase 2 of the Stripa Project focussed on methodologies for sealing these possible pathways using highly compacted bentonite (HCB).

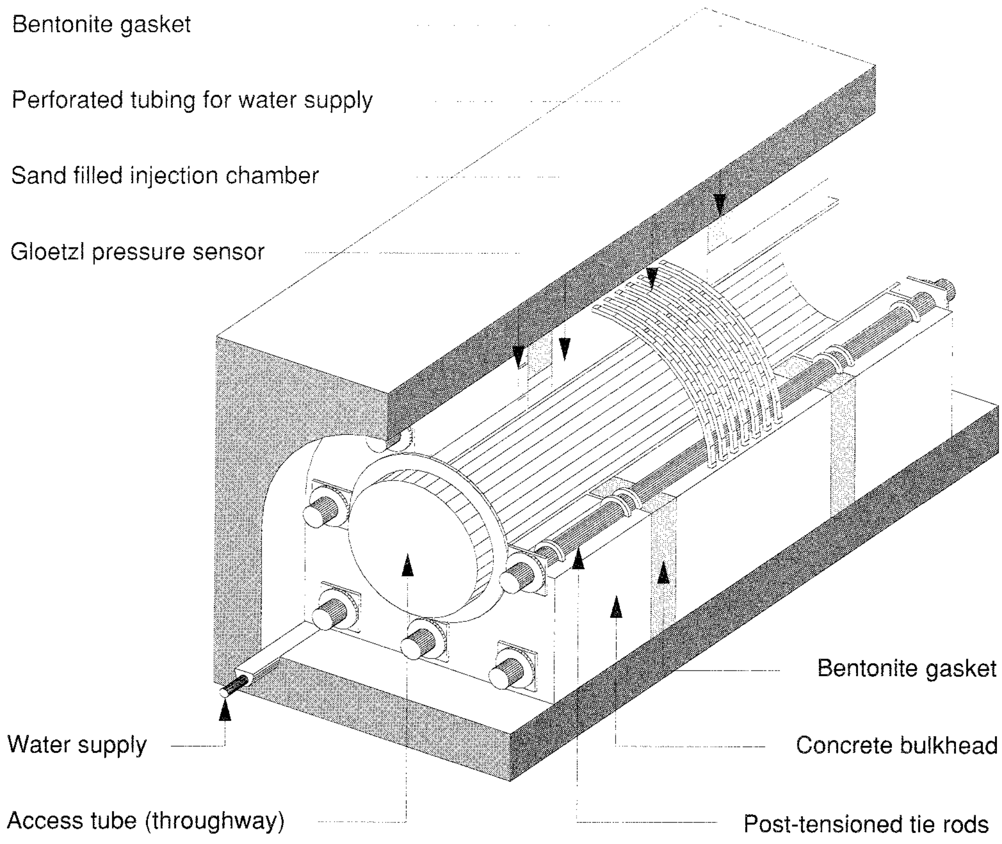


Figure 5-2. The layout of the tunnel plug test (after Pusch et al, 1987c).

HCB was placed as blocks on the inner faces of two tied concrete bulkheads. The inner steel tube (∅ = 1.5 m) provided access to the inner bulkhead. Such a structure may be used to seal off fracture zones during repository operation and provide access for equipment and manpower.

In the tunnel and shaft plugging experiments, highly compacted bentonite blocks, with densities and thus with properties similar to the buffer material tested in the BMT (Phase 1), were used. The tests were configured to determine the efficiency of swelling clay in limiting flow at the interfaces between bulkheads, backfills and the excavated rock surfaces. The layouts of the tunnel and shaft plugging tests are shown in Figures 5-2 and 5-3.

In both cases, two bulkheads were constructed within the excavations to form a test cell. The inner surfaces of the bulkhead were lined with HCB and the enclosed volume was filled with sand. The inner, sand-filled part of the test cell acted as a constraint to resist bentonite swelling and could be filled with water and pressurized. Only one tunnel plug test was carried out in which the hydraulic competence of the complete concrete bulkhead and HCB gasket was tested. Two shaft plug tests were conducted: the first tested the hydraulic properties of a concrete bulkhead alone; the second measured the hydraulic performance of HCB gaskets, confined within tied steel plates.

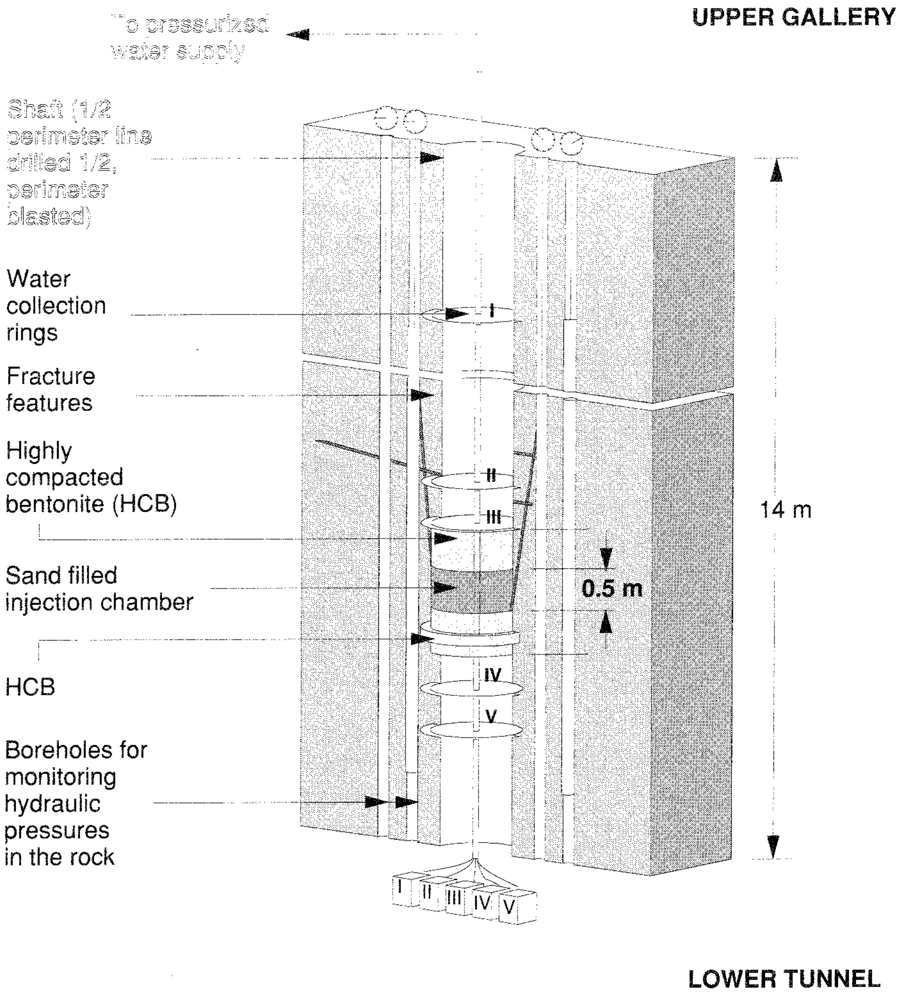


Figure 5-3. The layout of the shaft plug test (after Pusch et al, 1987b).

Concrete bulkhead performance was first tested. A plug consisting of HCB confined by tied steel plates was then tested. The second test showed that the HCB plug had a lower hydraulic conductivity than the concrete alone. Water was lost from the test cell through the neighbouring rock.

The hydraulic tests on the constructed cells lasted approximately 12 to 24 months. The tests involved increasing or decreasing the water pressure in the sand by steps, and measuring water flows into and out of the systems. The swelling properties and water uptake of the HCB were measured. The measured responses of the system and, specifically, the HCB were compared with predictions of performance derived using laboratory data, theoretical considerations and the experience obtained from the BMT (Phase 1).

The ease with which the HCB gaskets were placed showed that the concept of incorporating these materials into designs for plugs for large excavated openings was practical.

The hydraulic testing of the tunnel plug showed that after water uptake and swelling, the HCB effectively sealed interfaces between the bulkhead and the rock and minimised water flows at the HCB/concrete interfaces. The effective hydraulic conductivity of the combined concrete tunnel plug and HCB gasket can be estimated to be between 10^{-12} m/s and 10^{-11} m/s. This is of the same order of magnitude as the measured hydraulic conductivity of the undisturbed granite. Similar results were obtained from the shaft plugging tests, from which the effective hydraulic conductivity of the concrete plug and rock/concrete interface could be estimated to have been reduced significantly by the addition of the HCB gasket.

The measurements of water uptake by the HCB generally confirmed the applicability of isothermal diffusion models derived from laboratory tests and applied in Phase 1 for the BMT. An isothermal water diffusivity parameter value of $4 \cdot 10^{-10}$ m^2/s could be used reasonably to predict moisture profiles in the maturing (wetting) HCB. The water uptake measurements also showed that presumably, at an early stage of the tests, before swelling of the bentonite had occurred, water had flowed around the HCB gaskets. This pathway had subsequently been sealed.

Three borehole plugging/sealing tests were carried out. Each test was configured to allow for investigation of different aspects of borehole plugging with HCB.

In all of the tests HCB (MX-80) was introduced into smooth-walled, diamond- drilled boreholes and observations were made on the rate of maturation (water uptake and swelling) of the HCB, the resistance of the maturing bentonite to piping under hydraulic gradients, and the shear resistance between matured bentonite plugs and the borehole wall. The differences among the three tests lay in the orientation of the boreholes (one horizontal borehole and two vertical boreholes were sealed) and in the type of plug used (one vertical borehole was plugged using techniques which were virtually identical to those used in the horizontal borehole; a different sealing system was used for the second vertical borehole).

In all cases, the sealing system consisted of hollow cylinders of HCB encased in a copper exoskeleton, consisting of either perforated tubing or mesh. The exoskeleton provided needed rigidity to the system as it was inserted into the borehole. The perforations allowed access of water to the HCB, causing the material to swell and seal unfilled sections of the boreholes. This process is shown in Figure 5-4. The axial central hole in the HCB allowed access for instrumentation leads and hydraulic tubing.

The horizontal borehole plugging test was carried out in a 96.6-m-long, 56-mm-diameter borehole that was drilled as part of the SAC macropermeability experiment. The hole ran approximately parallel to and then continued 50 m beyond the end of the drift used for the BMT.

The vertical borehole plugging tests were carried out in two 14-m-long, 76-mm-diameter boreholes that were specially drilled between two vertically separated, parallel tunnels near the BMT area. The lower tunnel provided access to the 3-D migration experiment area.

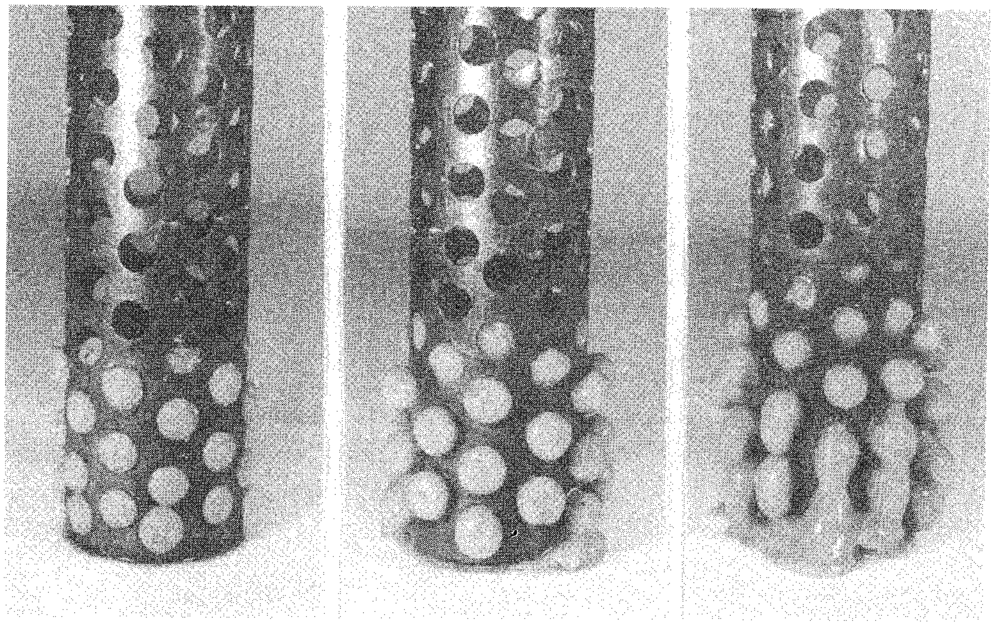


Figure 5-4. Evolution of an HCB plug.

(a) HCB contained within a perforated copper sleeve, and the effects of immersing the sealing system in water for (b) 8 hours and (c) 24 hours showing the extrusion of the bentonite through the perforations.

The layout of the vertical borehole plugging tests is shown in Figure 5-5. The test arrangement included mechanisms that allowed the plugs to be subjected to high water pressure gradients so that the hydraulic properties of the sealed borehole could be examined. The resistance of the maturing bentonite to piping was specifically investigated by applying high hydraulic gradients along the length of the plug and measuring the resulting flows. Moreover, total and pore water pressure sensors were included at strategic locations along the length of the plugs to assist with the interpretation of the flow measurements and to confirm aspects of bentonite behaviour and properties. The horizontal plugging test included filters at selected locations to allow for the hydraulic tests to be carried out. No pressure sensors were used in the horizontal plug test. After the *in situ* hydraulic testing of the borehole plugs had been completed, the vertical borehole plugs were extruded and measurements were made to evaluate the water uptake and swelling behaviour of the HCB. Owing to the configuration of the test, the horizontal borehole plug could not be extruded. At the end of the test a small volume of rock, through which the sealed borehole passed, was carefully excavated and the bentonite contained in it was examined.

The ease with which the borehole plugs were emplaced (it took only two hours to place the horizontal borehole plug) demonstrated the practicality of the design of the HCB sealing system for both horizontal and vertical borehole plugging operations.

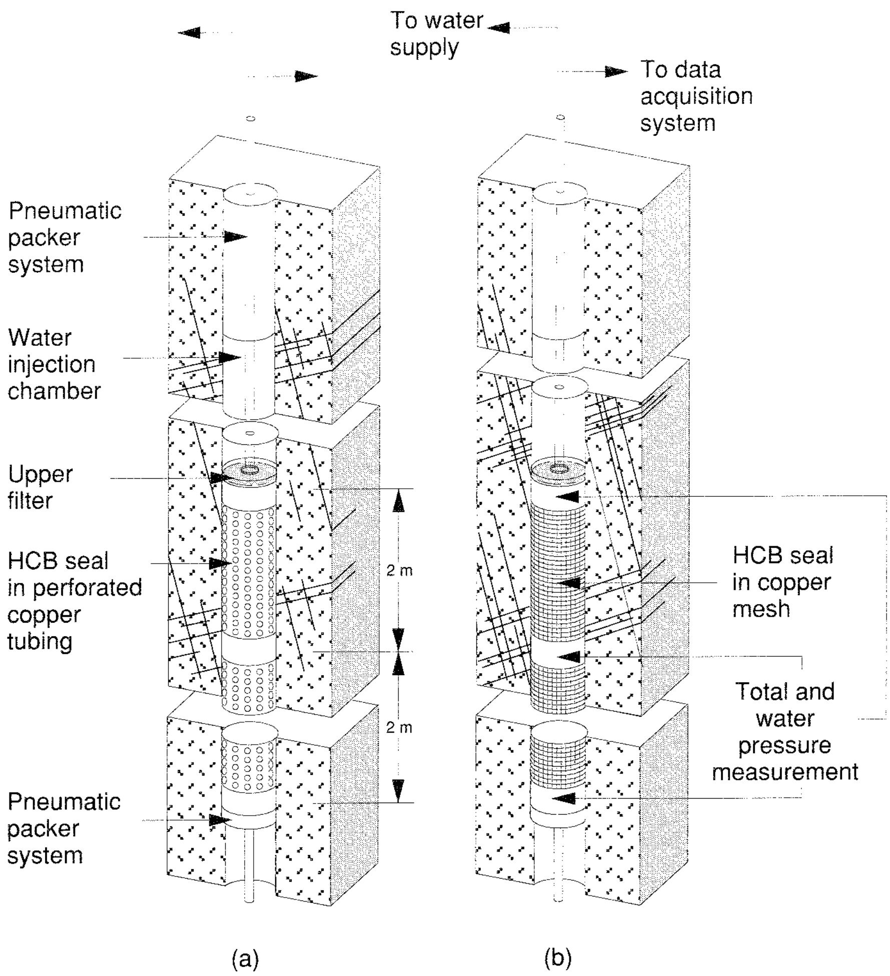


Figure 5-5. The layout of the vertical borehole plugging tests.

Two types of plug were tested (Pusch et al, 1987a). One [(a) above], similar to the system used in the horizontal borehole plugging test, was encased in a perforated copper tube. The other [(b) above] was encased in a copper wire mesh. Both systems effectively sealed the boreholes. System (a) was more rigid and the investigators considered it easier to emplace than system (b).

Hydraulic testing of the horizontal plug as little as 14 days after plug installation proved that the partially matured bentonite plugs could sustain hydraulic gradients as high as approximately 450 (4.5 MPa along 1 m of plugged borehole) without piping. The effectiveness of the seal at the HCB/rock interface was well demonstrated by the instrumentation used in the vertical borehole plugging tests. The centrally located instruments registered virtually no transfer of pressure (total or pore water) from the upper water filled and pressurized chamber.

Examination of the recovered HCB plugs further indicated that the clay was virtually fully water-saturated and had expanded into the annular space between the plug and the borehole wall that was needed as a working clearance (1 to 4 mm) during plug emplacement operations. This outer film of bentonite was less dense than the inner core, indicating either incomplete maturation and consolidation of the bentonite or an ability of the bentonite to sustain significant stress gradients. The hydraulic conductivity of a borehole sealed with HCB was concluded to be between 10^{-12} and 10^{-13} m/s, which is as low as or lower than that of the intact granite at the experimental levels in the Stripa mine.

In the analyses of the BMT carried out in Phase 1, it was clear that the interactions between the rock and the bentonite strongly influenced the behaviour and function of the engineered barrier materials. Self-injection of the bentonite into fractures under the forces generated during maturation and swelling, although limited in extent and not detrimental to long-term system performance, changed the hydraulic boundary conditions acting on the clay. Similar phenomena were observed in the borehole, shaft and tunnel sealing experiments. Despite the presence of discrete fractures in the rock, the bentonite appeared to take up water uniformly and was observed to have self-injected into the wider rock fractures. Moreover, the swelling of the clay sealed construction joints in both the gaskets used in the tunnel and shaft plug tests and the borehole plugging systems. It is particularly significant that in the tunnel plugging experiment, after maturation of the bentonite and during the hydraulic conductivity testing, most of the leakage from the test cell occurred through a moderately fractured, hydraulically conductive planar pegmatitic feature, about 1 m thick, that had been intersected by the excavations. Responding to this observation, and recognizing that such variability can be expected in rock masses hosting real repositories, initial attempts were made to seal the transmissive rock by grouting with bentonite clay. This measure successfully reduced outflow from the test cell by more than 50%. This first stage of the development of grouting materials and methodologies was to become the main focus of the Phase 3 investigations into engineered barriers.

5.4 PHASE 3 – GROUTS AND GROUTING

Phases 1 and 2 of the project demonstrated that excavations could be filled with materials capable of reducing the hydraulic conductivity of the excavated zones to values typical of undisturbed Stripa granite. Seals at the interfaces between the excavated rock surfaces and the engineered barrier materials could be secured by means of swelling clays. Evidence from work carried out at Stripa through the SAC programme and Phases 1 and 2 of the international project, combined with observations being made elsewhere, led to a conceptual model (Figure 5-6) that envisaged the possibility of the natural barrier to radionuclide release being bypassed by short circuits generated by the excavation disturbed zones surrounding the excavations. In this context, the SAC investigations and observations made during Phase 1 had shown that, relative to the natural properties of the host granite, the excavation disturbed zone (EDZ) may possess higher hydraulic conductivity along the axis of a tunnel and lower hydraulic conductivity radially away from the excavations. These phenomena were explained as related to the effects of rock-stress reorientation and concentration caused by the creation of the opening.

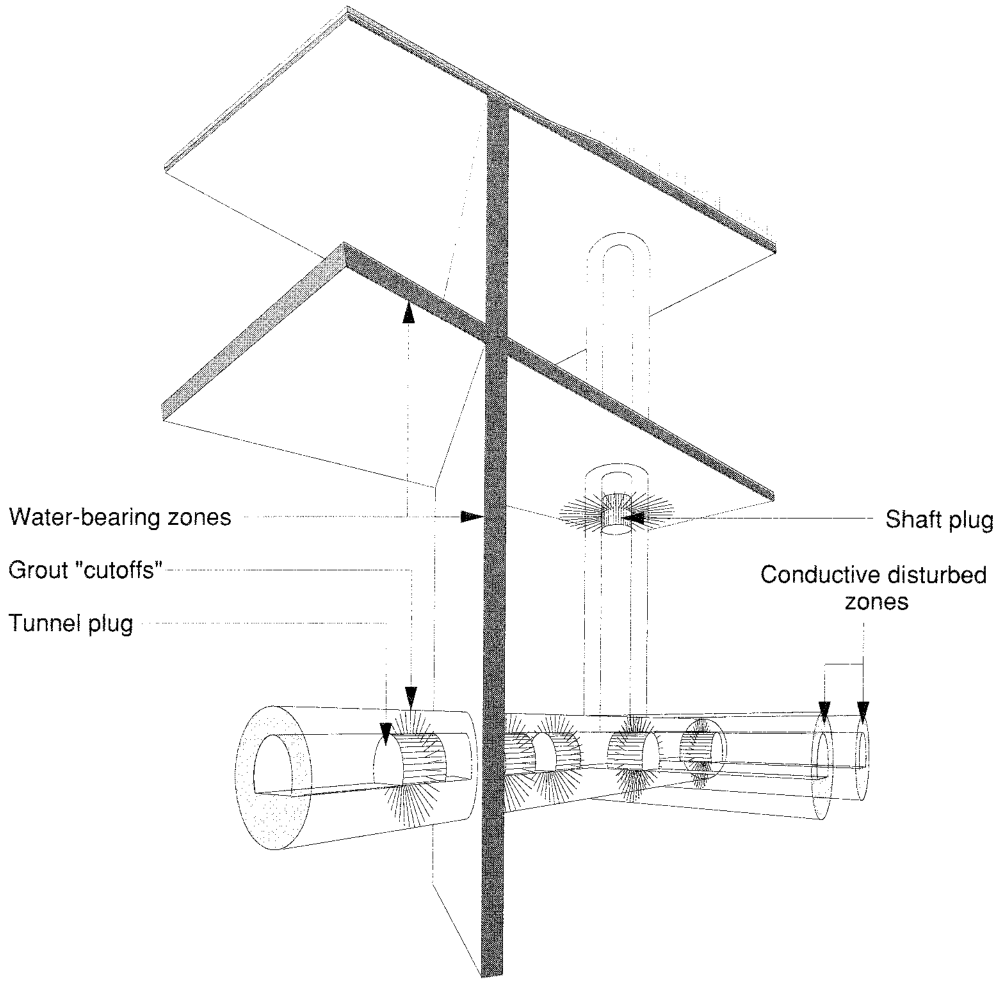


Figure 5-6. A conceptual model of major pathways for water flow in a repository.

This model was developed and discussed at two OECD/NEA Workshops (OECD/NEA, 1989a and 1989b). The EDZ can be seen to connect either directly to the surface or to the hydraulically active fracture zones that through Phases 1 and 2 had been identified as significant by investigations of the natural barrier.

Similar phenomena observed during the SCV exercise have been accounted for, qualitatively, by similar reasoning. The following alternative mechanisms for the phenomena have also been suggested (Hodgkinson, 1992):

- desaturation of the rock near the excavation surface, which was associated both with degassing of the groundwater as pressures decreased near the excavations and with the generation of gases by the combustion of explosives;
- high pressures produced during blasting, which drive water away from the excavations; and
- mineral precipitation and formation in fractures near the surface of the excavation phenomena associated with changes in hydrogeochemical conditions arising from the excavation.

Because the information available from Phases 1 and 2 on the properties of the EDZ was limited, further measurements and observations on its characteristics were needed. Moreover, with the still unproven, but conservative, assumption that the EDZ is detrimental to the isolating capacity of a repository for heat-generating radioactive waste, materials and methods to decrease the hydraulic conductivity of the zone(s) were sought. An extensive review of materials being investigated in the national programmes was undertaken (Coons et al, 1987). This identified grouts based on clays, portland cements and bitumens as potentially suitable for sealing the fine fractures anticipated in the EDZ, and therefore appropriate for study in the Stripa programme. Reflecting national interests and the requirement to limit costs, the Phase 3 investigations were limited to grouting materials based on clay and portland cement.

The following activities were undertaken to address major areas of concern identified by the review:

- *Laboratory studies* of material properties, to permit the selection of grouting materials and the design of appropriate grouting equipment and procedures.
- *In situ testing* of selected grouting materials and methodologies in both the EDZ and zones of moderately fractured and hydraulically conductive rock.
- *Evaluation* of the longevity of both cement- and clay-based grouts.

With regard to the latter, reasonable arguments may be needed to demonstrate that the performance of engineered materials used in repository construction is assured for many millennia. The review highlighted a number of issues for both clay- and cement-based sealants that could be resolved through exposure in the Stripa programme.

Section 5.4.1 reviews the work carried out for the implementation of the *in situ* studies. Section 5.4.2 presents a brief description of the work on sealant longevity.

5.4.1 *In situ* investigations

Within the context of the observational method as applied to geotechnical engineering, the *in situ* sealing investigations and experiments carried out in Phase 3 had the following primary objectives:

- to define the hydraulically significant characteristics of the EDZ and zones of moderately fractured, water-bearing rock; and
- to develop, apply and define the limitations of selected grouting materials and methodologies for application in repository design and construction.

Prior to conducting the *in situ* work, extensive laboratory testing, concentrating on the rheological properties of both cement- and clay-based grouting materials, was effected. The clay grouts were developed from the bentonite materials examined in Phases 1 and 2 of the project. The cement grouts were developed from materials that had been investigated through a joint USDOE/AECL project for the Underground Research Laboratory in Canada (Gray and Keil, 1989).

At the outset of the investigations it was expected that both the clay- and what later became known as "high-performance" cement-based grouts would be thixotropic. This specific aspect of grout rheology was investigated and, assisted by theoretical and numerical modelling of the processes of grout injection, devices were designed and built to take advantage of this material property during injection. These tools allowed for vibration of the grouts during injection, causing the materials to liquefy and thereby permitted injection at minimum water contents. Both cement- and clay-based grouts are made fluid by suspending the colloidal solids in water. Decreasing the quantity of water required for liquidity increases the density of the injected grout and enhances performance. An extensive database on material properties was established that allowed for the appropriate selection of the materials to be used in the *in situ* studies.

The *in situ* experiments were carried out in the BMT room, where the EDZ was studied, and in the 3-D migration drift, where moderately fractured rock was investigated. The choice of these areas of the mine was favoured because both had been investigated previously in the project and thus their characteristic hydraulic features had been identified, with various levels of uncertainty. Studies in the BMT room focussed on the end of the room in and around heater holes 1 and 2 (see Figure 5-1); the wet, eastern arm was studied in the 3-D migration drift. Developing studies of the natural barriers during the progress of the sealing experiments provided additional information on the major hydraulic features of the rock in the vicinity of the 3-D migration drift.

The principles of the tests planned for the BMT room are shown in Figures 5-7 and 5-8. Those for the tests in the 3-D migration drift are shown in Figure 5-9.

Using the specially developed injection devices, the test shown in Figure 5-7 was completed. Hydraulic testing prior to grout injection showed a clear increase in the hydraulic conductivity of the rock with increasing proximity to the surface of the excavation. Ungrouted, the rock had hydraulic conductivities in the range from $5 \cdot 10^{-10}$ to $5 \cdot 10^{-7}$ m/s. The higher values were reduced by grouting. Before heating, the hydraulic conductivity was reduced to less than 10^{-9} m/s. Heating caused the hydraulic conductivity of the grouted rock to increase to values that were intermediate between those of the untreated and the treated, but not heated, rock. Subsequent careful excavation of the grouted rock confirmed that the clay had penetrated the rock fractures, particularly those closer to the tunnel floor. This finding confirmed the hydraulic conductivity test results, which indicated that the grouting was more effective near the rock surface than distant from it. The

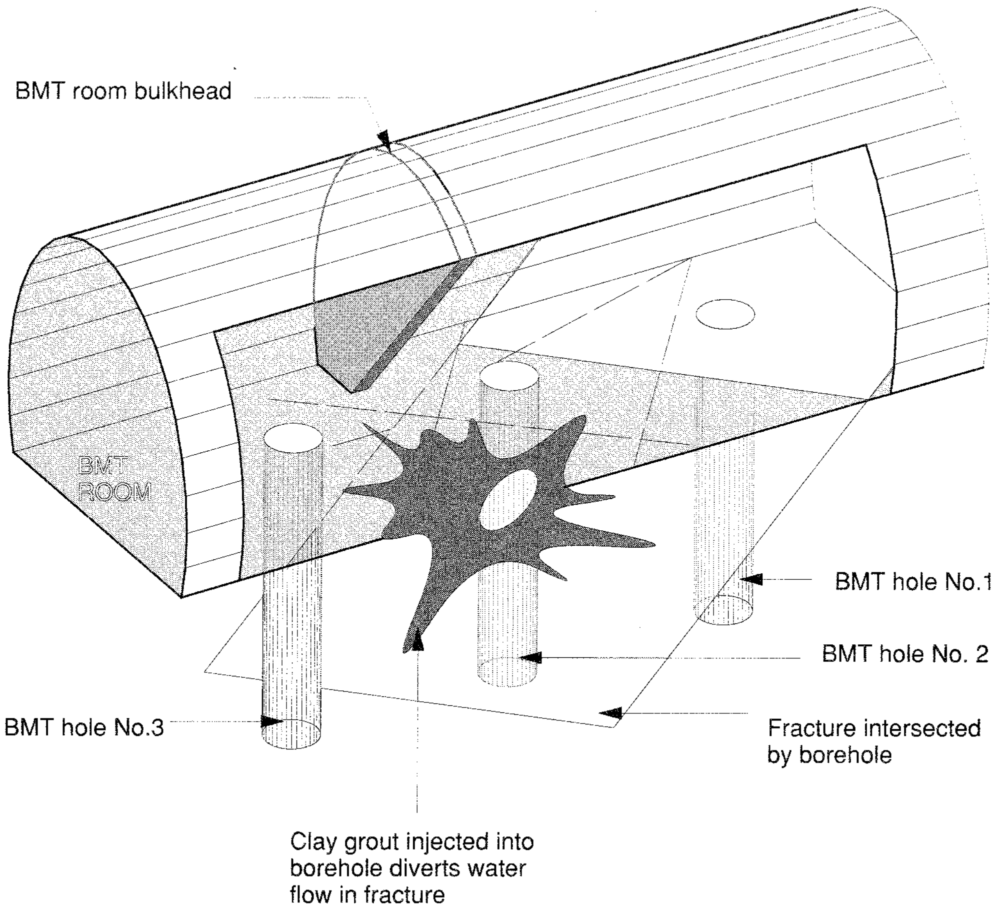


Figure 5-7. Sealing around emplacement boreholes (after Börgesson et al, 1991).

During the BMT (Phase 1) discrete water bearing fractures intersecting the emplacement boreholes had been identified. These were both natural and caused by excavation disturbance. A test was carried out to determine the extent to which these fractures could be sealed by bentonite grout. Possibly, such grouting procedures may be applied during repository construction to enhance the near-field seals.

results indicate that it is possible to grout discretely fractured rock with an initial equivalent hydraulic conductivity as low as $5 \cdot 10^{-8}$ m/s.

Employing an equivalent porous medium, finite element model, inflows into different parts of the test system shown in Figure 5-8 were calculated. The results of this flow model, which was symmetrical about the longitudinal axis of the tunnel, were checked against measured inflows at different stages of the test. This process showed that inflows into the test tunnel could be predicted with an accuracy of about 30%. The most consistent and accurate results were obtained using a model for the ungrouted rock that included a 0.5-m-thick blast-damaged zone with an isotropic hydraulic conductivity of $1.2 \cdot 10^{-8}$ m/s. The blast-damaged zone was surrounded by a 2-m-thick, anisotropic stress-disturbed zone with an axial hydraulic conductivity of $9 \cdot 10^{-10}$ m/s and a radial hydraulic conductivity of $2.3 \cdot 10^{-11}$ m/s. These latter figures were slightly modified locally to improve accuracy. The

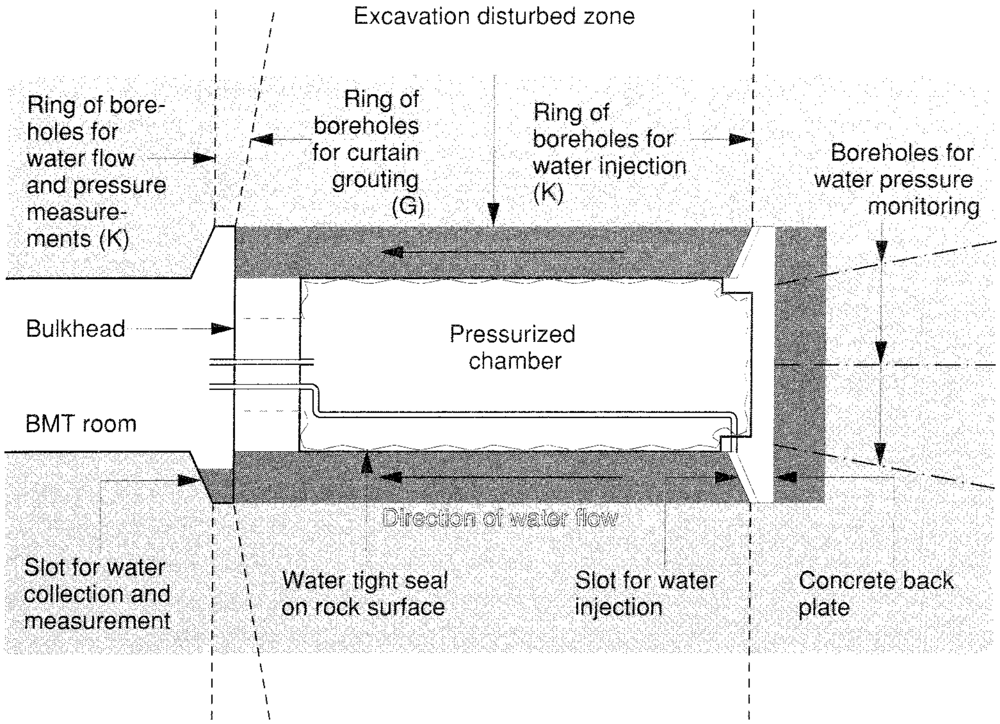


Figure 5-8. Investigating the excavation disturbed zone (EDZ).

The inner section of the BMT tunnel was to be sealed with a water tight lining and pressurized. Two rings of monitoring boreholes (K) were packed off in sections. This allowed for cross-hole hydraulic testing and, in combination with the end slots, for evaluation of the axial hydraulic conductivity of the EDZ, which was inferred from numerical simulations and testing to consist of a blast damaged zone and a zone influenced by stress relief. The effectiveness of cement grouts in sealing these two zones was examined. Testing of the grouting of the stress influenced zone (through the G holes) was not completed (Börgesson et al, 1992a, 1992b).

undisturbed rock was assigned isotropic hydraulic conductivities in the range from $3 \cdot 10^{-11}$ to $9 \cdot 10^{-11}$ m/s, depending on position and according to field measurements. The ability of the model to predict water flows and pressures at different stages of the test provided significant support to the empirical observations on the nature of the EDZ, and it was concluded that these observations were probably correct (i.e., the stress-disturbed zone in the BMT area of the Stripa granite is hydraulically anisotropic). Measurements indicated that the hydraulic properties of the stress disturbed zone were not symmetrical about the tunnel axis. This factor may account for the inaccuracy of some modelling results. Moreover it clearly demonstrates the presence of complicating natural factors that cannot be expected to be accounted for in performance models for a repository. It is not reasonable to expect that these local uncertainties can be evaluated during repository construction in the level of detail achieved in the Stripa studies. The possible existence of such local variations can be accommodated through uncertainty analyses and the use of appropriate safety factors in repository design.

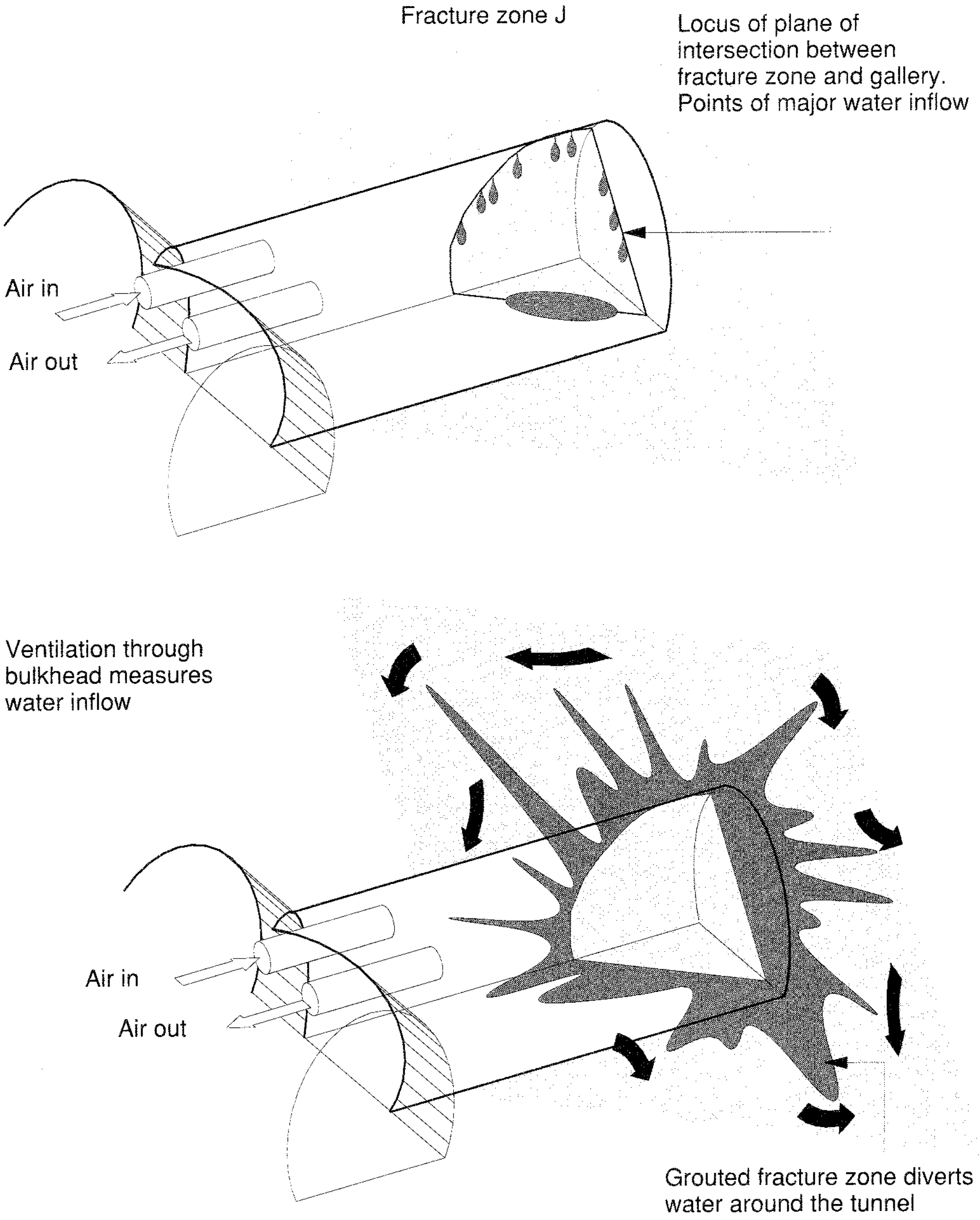


Figure 5-9. Concept for testing the efficacy of grouting a zone of moderately fractured, water-bearing rock.

A ventilation test was to be carried out to determine the water inflow into a rock chamber that was isolated from the rest of the mine. The major water bearing features were to be grouted (with cement grout) and the consequent changes in water inflow were to be determined by further ventilation testing (Pusch et al, 1991a).

Attempts were made to decrease the hydraulic conductivity of the shallow blast-damaged zone by injecting high-performance cement-based grout through shallow injection holes drilled at very close spacing into the walls of the excavation. Hydraulic testing indicated that this grouting procedure did not significantly change the hydraulic properties of the EDZ. Examination of samples of the grouted rock recovered by subsequent excavation revealed that although the grout had penetrated fissures as narrow as 40 μm, a continuous grout seal had not been generated. The grout readily penetrated new fractures generated by the blasting, but did not penetrate very well the natural fractures that contained infilling materials which obstructed grout flow and penetration. It is not certain that this result would have been obtained had it been possible to use high grout pressures. It was not possible to use high pressures when grouting the blast-damaged zone because of its close proximity to the free face of the excavation. Higher pressures than those used (800 kPa) could have significantly disturbed the rock. It was generally concluded that it was not possible to decrease the hydraulic conductivity of the blast damaged zone with the grouting procedures used. Alternative configurations for grouting or otherwise sealing off the EDZ remain to be examined.

Although simple in concept, as shown in Figure 5-9, the test to determine the ability of cement-based grouts to decrease hydraulic conductivity of moderately fractured, hydraulically conductive rock increased in complexity as more information became available on the rock properties through the progress of the investigations. The test proceeded on the initial assumption that the major conduit for water inflow into the excavation was fracture zone J, which was identified by the geophysical and hydrogeological investigation methods used in the natural barrier studies for the SCV exercise. Along with extensive geological characterisation of the rock in the test area, measurements of water pressure and flows before and after an initial attempt to grout the wet rock intersected by the excavations revealed that while the J zone provided water regionally to the area of the test, the local hydrogeology was influenced by a subordinate fracture system. This subordinate system was only identified by the engineering activities associated with the grouting programme, which involved extensive drilling into the rock and probing of the hydraulic features. This experience defines the limitations of the large-scale hydrogeological characterisation methodologies developed through the Stripa Project, and clearly indicates the need for engineering designs for repository systems to be allowed to evolve with the increasing knowledge of the rock mass that will be gained through the engineering activities associated with repository construction.

The hydraulic structures were grouted with high-performance cement-based grout in two stages. As noted above, the first stage provided results that led to an increased understanding of the important hydraulic features in the rock mass; the second stage was effected in an attempt to alter the water flow paths. This was successfully accomplished. Although the total inflow into the test area was not significantly decreased, water inflow in the rock was diverted around the grouted rock volume. It is considered that, as shown by other experiments (Gray and Keil, 1989), continued grouting could have successfully decreased the hydraulic conductivity of the accessible volume of the hydraulic structure from approximately 10^{-7} m/s to $5 \cdot 10^{-10}$ m/s or less. On the other hand, the practicality of grouting fracture zones in actual repository conditions remains to be established. Cores taken from the grouted rock contained cement-filled fractures. The morphology of the hardened cement was examined in detail and the knowledge gained of the material structure was used in the appraisals of cement grout longevity discussed in the following section.

5.4.2 Longevity of sealing materials

Longevity has been defined as the ability of a material to maintain its design performance through time, under the range of temperatures, pressures and geochemical conditions in the host environment. Implicitly, this definition accommodates the inevitable changes expected in sealing materials through time, with the requirement to understand the nature of possible changes and the consequences of these changes on sealing and, thus, total repository system performance.

Although some minor studies were undertaken as part of Phases 1 and 2 of the Stripa Project on aspects of the longevity of HCB seals, much of the available information on the important properties of both cements and clays rested within the national programmes for repository development. The review of sealing materials (Coons et al, 1987) revealed a general consensus that HCB would behave adequately for millennia at temperatures below about 120°C. No such consensus existed for either the less dense clays to be used as grouting materials or for the portland cement-based materials. Studies were undertaken to reduce uncertainties about these materials.

For bentonite-based materials, attention focussed on providing detailed understanding of hydrothermal alteration of the mineral; particularly, reactions causing transformation of smectitic clays to hydrous clay-micas or causing cementation of the clay mass were studied (Pusch et al, 1991b). Both of these processes could decrease the swelling capability of the bentonite and lead to a loss in long-term function. For the cement-based sealants, mechanisms causing dissolution of cement in groundwater and, thereby, an increase in the hydraulic conductivity of the grouted rock were investigated: specifically, the leaching and hydraulic conductivity properties of the materials were studied. To allow for the development and application of theoretical and numerical models of cement-grouts longevity, a database on the fundamental thermodynamic properties of cement grout phases was established and expanded. In addition to these basic studies, the mechanical stability of clay gels and unset cement pastes were investigated to determine their ability to resist erosion under the action of flowing groundwater. This information was needed to define the limiting groundwater flow conditions under which each of the materials could be applied.

To a greater or lesser extent, depending on applicability and the issues being investigated, the following three basic methodologies were applied to investigations of the longevity of both the clay- and cement-based materials:

1) investigation of natural analogues and archaeological evidence;
2) laboratory studies of basic material properties; and
3) application of the principles of thermodynamics.

Studies of the morphology of grouts recovered from the injections in the Stripa mine allowed the theoretical models to be adjusted to reflect actual, rather than supposed, material fabric.

The crystal structures of smectite minerals and hydrous clay-micas possess similar features. With particle sizes less than 2 μm, both mineral types consist of negatively charged lamellae of phyllosilicates comprised of covalently bonded silica (2 outer) and alumina (1 inner) layers. The lamellae in clay-mica are ionically bonded by K^+. In smectites the lamellae are separate and discrete. Studies of the products of reaction between bentonite, finely ground silica, groundwater and rock over a wide range of temperatures and pressures showed that when K^+ is present in the groundwater, the smectite in bentonite clay grouts will convert to hydrous mica. In contrast with HCB, for which the conversion reaction will take many tens of thousands of years, conversion in clay grouts will take a few thousands of years or less. At temperatures above about 130°C, the conversion reaction will be accompanied by the release of silica from the clay crystals and the precipitation of the silica within the clay fabric. This latter process results in cementation and embrittlement of the grout. The benefits gained by the use of flexible, swelling clays will be lost. The cementation reaction is enhanced by the presence of silica powder. Thus, while the studies showed that admixing siliceous rock flour with the clay improves the mechanical performance (piping resistance) of fresh clay-based grouts, siliceous additives to clay grouts may not be appropriate for applications aimed at sealing repositories for heat-generating radioactive waste, where temperature may exceed 75°C. The effects of the conversion of smectite to hydrous clay-mica on the performance of a grouted rock mass were assessed by reviewing the structure of the grouts uncovered during examination of the samples recovered from the *in situ* tests. It was estimated that after the grouted rock mass has undergone complete conversion from smectite to hydrous claymica, it will still possess an hydraulic conductivity that is significantly less than that of the ungrouted rock. The Stripa studies suggest that this process is controlled by the coefficient of Fickian diffusion of K^+ in the clay and the concentration of K^+ in the groundwater.

High-performance cement grouts differ from normal cements and concretes. First, high-performance cement is ground to an average particle size smaller than that of ordinary cements and allows for penetration of fine fissures. Second, it contains two performance-enhancing additives: superplasticizer (which increases the fluidity of the grout at low water/cement ratios) and pozzolanic material (finely divided particulate and amorphous silica, which, by reaction, decreases the amount of free $Ca(OH)_2$ in the hardened grout). Theoretically, both additives enhance the durability of the materials. A lower water/cement ratio results in denser, stronger, less permeable material; reduced $Ca(OH)_2$ decreases the solubility of the hydrated cement solids in groundwater. In contrast with bentonite and normal portland cements and concretes, high-performance grouts are relatively new (development began only in the 1980's) and, at the outset of Phase 3, information on basic properties such as hydraulic conductivity, microstructure and resistance to environmental forces of degradation was scant. Laboratory studies were undertaken to begin to provide these data. These studies were coupled with geochemical modelling of the changes that may occur within the fabric of the material and a numerical assessment of the effects of these changes on material performance. In the absence of other information, the modelling studies were based on contemporary understanding of normal cements and concretes, with adjustments for expectations of laboratory findings on the high-performance materials. Figure 5-10 shows the links between modelling and laboratory studies on the longevity of cement grouts.

Using the database available at the early stages of the investigations, the longevity model predicted that the grouts would endure between 100,000 and 1,000,000 years in a repository environment. The model was simplistic in that it did not account for the complex amorphous nature of some of the siliceous and aluminous phases found in cement, nor for the existence of unhydrated material and hydrated lime that was found to exist in high-performance grouts in the form of portlandite. Unhydrated materials were also found to exist in ancient cements. Later developments of the model were able to incorporate portlandite in the normative composition of the model for the hydrated cement phases.

The porosity-hydraulic conductivity relationship for conventional portland cements was found not to apply to high-performance materials, laboratory specimens of which were shown to be virtually impermeable at hydraulic gradients less than approximately 15,000. It is noted that with the mine working open, the maximum hydraulic gradient measured in the Stripa facility was approximately 2000; much lower gradients are anticipated in a sealed repository. This has significant bearing on the findings of the studies. Based on conventional wisdom, it was assumed for the longevity models that cements would degrade by water percolating through the grouts; as the water passed through, the cement solids would dissolve and the consequent porosity increase would enhance hydraulic conductivity. This dissolution model now appears to be overly simplistic (Onofrei et al, 1992). Given the low conductivities achieved by high-performance cement grouts, substantial flow through the body of the cement does not appear likely. Rather, flow will probably be diverted to grout-rock interfacial gaps or into the surrounding rock. While flow will occur around the grout, diffusional processes will operate within the grout to alter the "mineralogy" and chemistry of the cement. This slow diffusional process virtually assures an approach to chemical equilibrium and means that void spaces represented by micro-cracks or other microporosity will be filled by the precipitation of secondary products (the chemical reaction of groundwater and cement yields secondary products that occupy more space than was occupied by the original solids).

The consequence of this new understanding is that during early repository history, cement grout performance will be dominated by surface-controlled mechanisms. Because these mechanisms are less efficient at mass removal than the processes assumed by the percolation/dissolution model, the calculated persistence times reported above are considered to be a lower bound on the longevity of intact cement grout. Several uncertainties rest with this

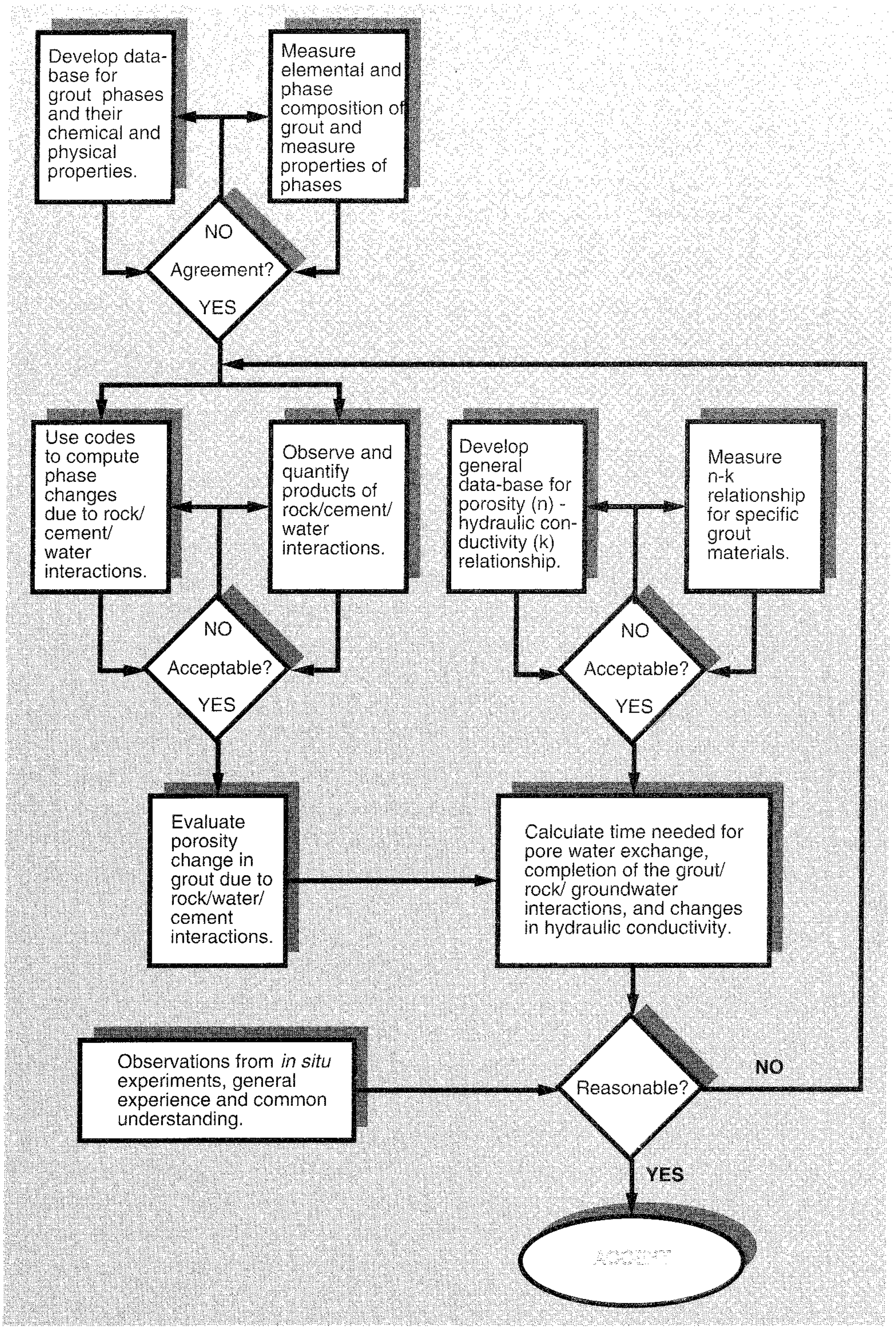


Figure 5-10. Flow diagram for the studies on longevity of cement-based grouts.

The laboratory studies showed that laboratory prepared grout specimens were virtually impermeable as a result of very small pore volumes and fine pore size distributions. Extremely low permeabilities are expected to enhance longevity by controlling surface processes such as leaching. It was shown that the naphthalene based superplasticizers are incorporated within the hydrated cement phases and are immobilized within the grout. The superplasticizers will not significantly contribute to the load of free organic matter present in a repository (Onofrei et al, 1991).

judgment. Particularly, examination of the microstructure of the grouts injected in the Stripa mine revealed an inhomogeneous structure that was not present in laboratory-prepared and -tested materials. These inhomogeneities have not been found in *in situ* investigations carried out elsewhere, and the full implications of the Stripa finding need to be appraised after further *in situ* tests have established wether the result is specific to the Stripa site and to the injection technique applied in the Stripa field tests. In common with other areas of investigation, the Stripa studies into cement grout longevity have highlighted matters of practical concern that may need to be investigated *in situ* by national programmes, possibly during site specific repository construction and development.

5.5 SIGNIFICANT ACHIEVEMENTS

The "observational method" (Peck, 1969) provides a basis for the investigation of the geotechnical engineering aspects of a repository for heat-generating radioactive waste. The method not only recognizes the need to observe important aspects of the rock mass and its response during repository construction, but also demands that engineering measures be available prior to construction to counter any reasonably foreseeable performance or safety concern. Some of these measures have been examined in the engineered barrier studies for the Stripa Project. The focus has been on the development of materials and methods for reducing the hydraulic conductivity of the engineered repository structure, including both the engineered openings and the accessible rock mass.

The application of both clay- and cement-based materials for sealing repositories has been considered, and limits have been defined for the longevity of these materials. It has been shown that, provided maximum temperatures do not exceed about 130°C, HCB and compacted bentonite-sand mixtures can be used to fill rooms and to seal boreholes, shafts and tunnels. These clay materials can be expected to perform effectively for tens, if not hundreds, of millennia. Less dense bentonite clay gels used for grouting rock will change to non-swelling clays within hundreds to several thousands of years. These non-swelling clays retain an ability to reduce the hydraulic conductivity of those elements of the repository system that have been treated. The longevity of cement-based materials cannot yet be as precisely prescribed as that of clay materials. However, it is reasonably certain that, applied as grouts in regions of a repository that are at temperatures below about 75°C, cement-based materials will persist in a repository environment, such as that exemplified by the Stripa granite, for very long periods of time, perhaps offering adequate performance for millions of years.

Practical methodologies for using highly compacted bentonite and compacted bentonite-aggregate mixtures to backfill engineered openings in the rock mass have been demonstrated. These methodologies result in sealed openings with hydraulic conductivities similar to those of the host Stripa granite ($\cong 10^{-11}$ m/s), ensuring that Fickian diffusion would be the dominant mechanism of radionuclide flux within the engineered components of a repository in which these backfill materials were employed.

Some of the complex phenomena involved in the processes of heat and water transfer that will occur in bentonite clay barriers when these materials are used close to heat-generating waste containers have been observed and elucidated. It is clear that water transfer under temperature gradients can significantly influence the processes of re-saturation of repositories built beneath the natural water table in the host rock. Phenomena similar to those observed during saturation of buffer and backfill materials and driven by temperature gradients may be relevant in unsaturated host media. The significance of these processes to the assessment of the performance of a repository and any need further to clarify the transfer processes must be judged on the basis of site-specific conditions and national regulatory requirements.

The water uptake and swelling properties of HCB can be effectively utilized to seal interfaces between rigid bulkheads, such as those made of concrete, and the engineered rock surfaces. Practical methods for placing such seals have been demonstrated, along with the ability of the clay systems to effectively limit water flow. Moreover, simple, practical designs for HCB systems for sealing investigation boreholes have been applied and demonstrated to be effective.

The extent to which the excavation geometry and processes influence the hydraulic characteristics of the Stripa granite have been examined. The study identified an excavation disturbed zone, composed of a blast-damaged zone immediately adjacent to the face of the excavations and a zone influenced by stress realignment and concentration surrounding the blast damaged zone. The disturbed zone did not possess the same hydraulic characteristics as the neighbouring host rock. Moreover, like the properties of the host rock, the properties of the disturbed zone were anisotropic and variable in the scale of tens of metres. Such variability can be expected in the host rocks for repository structures. It is not considered reasonable to expect that these local uncertainties can be evaluated during repository construction in the level of detail achieved in the Stripa studies. The uncertainties will have to be accommodated in any scheme for the approval of a repository design, which may have to be an iterative process to accommodate the observations made at the repository site.

Grouting techniques that were tried in the Stripa mine for treating the excavation damaged zone were not successful at decreasing its hydraulic conductivity. This experience may reflect the practical limits of grouting technology and, if such zones exist at a disposal site, their significance to repository performance will need to be assessed. It remains unclear whether or not decreasing the hydraulic conductivity of the blast-damaged zone improves repository system performance. Should decreased hydraulic conductivity of the excavation disturbed zone be needed, alternative methodologies to those examined through the Stripa investigations will have to be developed.

Major water flow paths in the accessible rock mass near the engineered openings were successfully grouted; groundwater was diverted around the grouted zones of moderately fractured rock. Thus, it may be possible locally to modify the groundwater flow paths to the benefit of total repository system performance or for construction expediency, if such action is deemed necessary. The grouting activities, like the studies of the interactions between clay backfills and the host rock, revealed significant details of the hydraulic features of the accessible rock mass. It became evident that the engineering activities associated with repository construction, operation and closure will provide information that can be used to understand and enhance the isolation capacity of a repository for heat-generating radioactive waste. This further reinforces the suggestion that detailed repository design should be an iterative process that accepts and responds to the increased knowledge of the natural barriers gained though the repository engineering activities.

6 LESSONS LEARNED

The Stripa Project improved the methodologies for the characterization of candidate repository sites and advanced the technology for sealing repositories. This progress has been achieved with the support of as many as nine countries over the thirteen years of the project. Further clarification of unresolved issues may be required as the knowledge gained through the Stripa Project is applied to specific sites. It is instructive to consider the technical and institutional features of the project that have contributed to the scientific accomplishments.

6.1 TECHNICAL

The principal investigators of the Stripa Project have been challenged by many technical issues and have worked to advance both specific knowledge, in fields relevant to the disposal of heat-generating radioactive waste, and more general scientific issues. The achievements noted in this report and all the technical documents that form the history and record of the project show significant success – and reveal some unresolved questions. It is important to recall that the prime purpose of the project was to develop technology to assist practitioners, licensing bodies and other interested parties in evaluating the suitability of sites and developing radioactive waste repositories. Viewed from these perspectives, the following major technical lessons can be drawn from the project.

Significant developments have been made in site characterization methods including seismic, radar and hydraulic testing tools and techniques. Limits remain, however, on the resolution to which dominant hydraulic features and structural properties of the rock can be identified and characterized. These limitations have to be considered during site characterization efforts and must be accounted for and accomodated in any performance assessment for a specific site.

The extensive data base required and the lack of available tools to identify natural variability made it virtually impossible to model deterministically the detailed hydraulic characteristics of the large volume of fractured rock that was investigated at Stripa. Models based on the stochastic and/or equivalent porous media approaches, combined with an appreciation of the dominant hydraulic features that can be revealed by available methodologies, offered a reasonable compromise.

Special consideration was given to the process of "validation", specifically in the context of evaluating the validity of numerical models for groundwater flow. A methodology for a validation process was developed and implemented. The success of the model validation exercise depended on the balance between expectations and practicality in relation to the quality of the input data and model complexity. While the success of validation is specific to work carried out at the SCV site in the Stripa mine, the rationale and the protocols used for the validation exercise may be suitable and applicable to many of the actions required to develop a radioactive waste repository. These include predicting the performance of both natural and engineered barriers.

The need to achieve low hydraulic conductivities through the use of engineered barriers, in either the excavations or the neighbouring disturbed rock, is not entirely evident and must be determined on the basis of site-specific and repository-specific assessments. In the event that such low conductivity seals are required, it was demonstrated that backfilling and plugging excavated openings in rock can be accomplished effectively. The hydraulic conductivity in the backfilled openings was returned to values similar to or lower than those of the undisturbed rock at Stripa. The ability to achieve the same hydraulic conductivities in the rock disturbed by the excavation remains uncertain, as do the other hydraulic properties of the disturbed rock.

The Stripa Project has increased knowledge of the properties of the Stripa granite and the effects of engineering activities on those properties. It is noteworthy that the understanding of the properties of the undisturbed rock mass was developed through studies of both the natural and the engineered barriers. Moreover, some experimental activities were modified in accordance with progressively revealed features of the rock (e.g., stress orientation and flow characteristics). It can be inferred that both site characterization and repository design should follow a similar iterative path. This adaptive approach would be valuable also in the programme towards licensing of radioactive waste repositories.

The experience of the Stripa Project shows that characterization of a candidate repository site can be time-consuming and may require significant resources, both financial and human. A core body of experienced geoscientists, geotechnical engineers and modellers has been established through the Stripa Project and associated national programmes. It is likely that this body will need to be enlarged further to meet the requirements of siting and construction of repositories. Each site-specific application may be able to employ some of the characterization and engineering methodologies developed at Stripa. However, it is likely that each site will have specific requirements that will necessitate unique developments and an expansion of the learning processes initiated at Stripa.

The principal investigators for the Stripa Project represented different scientific disciplines and had different motivations and perceptions. It was difficult to achieve and maintain an effective interface between the investigators involved with natural barriers research and those involved with engineering barriers investigations. The interface that existed over the course of the project was somewhat less than desired. In the actual process of siting and designing a repository, the interface must be established and maintained by management. To do less could seriously compromise the efforts to license and operate the repository.

6.2 INSTITUTIONAL

From the outset, emphasis was placed on the research nature of the project. Technical issues only were considered. As much control as possible was given to the principal investigators. The JTC was responsible for final approval of research projects and expenditures. The JTC met annually and considered research recommendations developed from discussions between the principal investigators and technical representatives from the member countries at the annual meetings of the technical subgroups. A project manager, with part-time assistance, coordinated the activities of fourteen to twenty principal investigators and managed the total budget of 257 MSK over thirteen years. This amount does not include significant contributions from individual member countries in supplemental research support to the Stripa investigations and in defraying other expenses, such as those incurred by the JTC, TSG, and task forces. The 173 technical reports provided a detailed record of the progress of the research over the thirteen years.

Research and development associated with radioactive waste disposal are influenced by international and intra-national political and legal sensitivities. These were accommodated within the Stripa Project. Attention was given to the promotion of technical advance within a framework that, as much as possible, allowed for the information gained to be transferred to the benefit of member countries. Procedures for gathering data and reporting observations were not formalized, but rather were left to the judgment of the principal investigators. The rigour of peer review applied to scientific publication and debate was accepted as appropriate for the project. The likelihood of errors was accepted as an inevitable drawback that went with the benefit of creative and innovative solutions to the questions being investigated.

To promote scientific and technical progress, primary emphasis was placed on the active involvement of respected scientists and engineers in the conduct of the project and, to the extent practicable, administrative procedures and bureaucratic control were minimized. The Stripa Project is a good example of what can be achieved when high professional standards and scientific credibility are emphasized and bureaucratic controls are minimized.

7 CONCLUDING REMARKS

The principal objectives of the Stripa Project, when it began in 1980, focussed on the development of techniques to characterize crystalline rock masses that are potentially suitable for the construction of a geologic repository for radioactive waste, and the examination of engineering design considerations to enhance the long-term safety of the repository. Over the course of some thirteen years, research activities to satisfy these objectives were planned and carried out, principally in the granitic rock mass that contained the Stripa mine. Tools and techniques to quantify the hydrogeologic characteristics of a saturated, fractured granite were developed and demonstrated to be effective. Conceptual hydrogeologic models of the Stripa mine and its surroundings were developed and used with reasonable success for simulations of groundwater flow and transport. The characteristics of clays and cements that were considered to be important for the effective long-term sealing of fractured rock and man-made excavations were studied through numerical simulations, laboratory studies and experiments in the Stripa mine. The knowledge that emerged from these studies is impressive in extent and detail, and is destined to have application in the design of seals for geologic repositories and other underground containment structures and systems in many rock types. The field-scale demonstrations of shaft and tunnel sealing, borehole plugging, and the use of clay buffer materials in a saturated environment at elevated temperatures were both comprehensive and innovative.

These are the tangible accomplishments of the Stripa Project. The transfer of technology from the project to the member countries, and among the member countries, is in itself a significant accomplishment and must not be overlooked. Certain aspects of research programmes in the member countries are reflections of the research activities, discussions and debates that took place. In addition to some conclusions from the work of the Stripa Project, this chapter looks forward to the possible focus of future research to support the development of geologic repositories.

7.1 CONCLUSIONS

The main conclusions of the Stripa Project are listed below.

1) Underground access to representative depth may be necessary for assessing the safety of a repository in crystalline rock and is required for the detailed characterization work required to design a repository.
2) Due to variability and uncertainty in the geological environment, the site characterization process should be iterative and adaptive.
3) Significant advances have been made in geophysical and related techniques for identifying water-bearing fracture zones in granite. Such zones were identified up to 100 m away from boreholes.

4) Flow of water in undisturbed, fractured rock occurred in only a fraction of the discontinuities identified. Fracture flow is not uniform; zones of practically stagnant water may exist between the complicated flow channels. The influence of these flow features on radionuclide migration may be significant, but difficult to quantify.
5) Both discrete fracture flow and porous media models were able to describe groundwater flows into the excavations in the Stripa granite and changes in hydraulic conditions caused by the creation of the excavations.
6) Excavations at Stripa were surrounded by a disturbed zone with a radial permeability lower than that of the undisturbed rock. Observations to establish whether or not permeabilities parallel to the excavation were increased gave contradictory results. The significance of these permeability changes to repository design and performance assessment will depend on site specific and design specific features. If necessary, engineered control of the excavation affected zone seems possible.
7) Measurements of several naturally occurring radionuclides have established that groundwater deeper than 600 m in the Stripa area has been isolated from the atmosphere for at least several thousand years and possibly more than a hundred thousand years.
8) The geochemical studies, among other results, have demonstrated that a number of radionuclides are generated underground, in uranium-rich rocks, in quantities that exceed the cosmogenic contributions.
9) Engineered barriers can be integrated in repository designs with the functions of: a) improving waste isolation, b) backfilling excavations and c) restricting access of groundwater to the disposal zone. Aspects of barrier construction and performance of sealing systems have been successfully demonstrated. The need to apply engineered barriers to the excavation affected zone should be assessed on a case by case basis, depending on specific features of both candidate site and repository design.
10) The confidence in the longevity of certain clay- and cement-based engineered barrier materials has been increased greatly by the Stripa Project.
11) International cooperation, in relation to radioactive waste disposal, has been effective and rewarding. The recommendation that interested countries and international organizations give serious consideration to other cooperative activities similar to the Stripa Project appears to be a logical consequence and a worthwhile objective.

7.2 FOCUS OF FUTURE WORK

As each country moves forward with its programme of repository siting and development, the specific features of the hydrogeologic setting and the rock type will dictate the requirements for characterization and design. However, some common factors among programmes and sites do exist. Dissolution and movement in groundwater are the mechanisms by which radionuclides are generally expected to reach the environment accessible to humans. The work at Stripa has demonstrated that the bulk of water in the Stripa granite flows in discrete zones in which the rock has been highly fractured by some form of tectonic activity in the distant past. In all likelihood, the detection of such zones at a candidate repository site, early in an exploration programme, would considerably affect the evolution of subsequent characterization activities and design efforts. The work at Stripa has shown that fracture zones contained within a few million cubic metres of a saturated granite can be detected, and that their geometric and hydraulic characteristics can be evaluated through the use of remote-sensing techniques in boreholes. The next logical step would be to extend this capability with the same reliability to the detection and characterization of fracture zones in rock masses with volumes ranging from tens to hundreds of million cubic metres.

The simulation of groundwater flow at Stripa by numerical modelling procedures was accomplished with reasonable success at scales ranging from a few tens of metres to a few kilometres. However, the outcome of the modelling of solute transport in the saturated, fractured granite was not as satisfying. The travel times of nuclides calculated from simulation models on a regional scale and those estimated on the basis of geochemical data were not in close agreement. It is not clear whether this lack of agreement was due to the assumptions of the mathematical formulation of the simulation models or to the lack of field data. A lack of maturity and experience in the use of newly developed methods of geochemical analysis may have contributed to some lack of precision in the time estimates. The agreement between calculations and measurements of tracer transport, apart from the travel times, was considerably improved at the local scale of the SCV site. The transport of a nuclide by groundwater flowing in a fracture zone is a complex process, and the characteristics of dispersion, retardation and channelling are difficult to quantify. The work at Stripa demonstrated the need to understand the hydrogeologic and hydrochemical characteristics of a rock mass before transport experiments can be conducted in a manner that allows the process to be understood. This first step is important because it indicates what must be known in order to design a transport experiment. The use of this methodology in the design of a tracer experiment will allow the transport mechanisms in a specific rock to be understood and quantified.

The research at Stripa demonstrated that boreholes and shafts in a saturated, fractured granite can be sealed with sodium bentonite to achieve a hydraulic conductivity similar to that of the host rock. The need to apply this technology to the design of a repository will depend on the site conditions and the safety assessment. From a practical point of view, future investigations might wish to evaluate more cost-effective methods of seal emplacement, and the trade-off in benefits between the use of bentonite, cement or other materials as a component of the seal. During Phases 1 and 2, bentonite clay was selected as the sealing material of interest; consequently the effectiveness of other materials was not evaluated under *in situ* conditions in the Stripa mine. Attempts were made in Phase 3 to work towards a more balanced view of the capabilities of different materials.

The emphasis on studies of the fundamental material properties of clays and cements in Phase 3 led to some significant findings. An extensive database was established from laboratory experiments to support the view that the chemical longevity of bentonite could be assured in repository environments over long periods of time when the temperature was below 80°C. Evidence from natural analogues was obtained in studies outside the Stripa Project to reinforce this view. Although the database developed for the high-performance cements suggested an acceptable level of chemical longevity, more research will be necessary to demonstrate this attribute in a more compelling manner. Moreover, a better understanding of the mechanisms of heat and moisture transport in highly compacted bentonite (HCB), and the influence of such transport on radionuclide mobility, are necessary before the effectiveness of HCB in retarding radionuclide transport can be firmly established.

The studies of the rheological properties of bentonite and cement provide a useful background for designing grout mixes that can be injected into a low-permeability rock mass and that will persist in a repository environment. The studies demonstrated that it may be easier to grout a high-permeability rock and achieve a state of very low permeability, than to reduce substantially the permeability of an already low-permeability rock. Further thought should be given, however, to the design and selection of equipment for grouting fractured rock on a production scale. In particular, the specific details of the injection techniques and conditions for grouting in a site-specific situation will need to be investigated.

The work at Stripa yielded a significant appreciation of the existence and extent of the excavation disturbed zone in the local bedrock. The measurements at the locations of the Validation Drift in the SCV site, the fracture zone intersecting an arm of the 3-D Migration Test drift and the SAC macropermeability test (BMT) room indicated that the hydraulic heads were changed and the pattern of groundwater circulation was altered in the rock mass after excavation. In the SCV site, the groundwater flow was diverted around the drift excavation, resulting in reductions of inflow to the drift. Whether these effects are site-specific, or even important to repository safety, remains to be established. Clearly, the excavation causes a redistribution of the stresses in the rock mass immediately surrounding the opening. However, the consequences may be rock-specific, or more sensitive to local variations in the properties and conditions of the undisturbed rock mass than to what happens in the rock immediately surrounding the excavation. The importance of the excavation disturbed zone from the viewpoints of design of engineering barriers and of long-term safety of the repository will need to be assessed on a site and repository specific basis.

7.3 FINAL REMARKS

As noted in the Introduction, demonstration that radionuclide transport from a repository to the biosphere will occur very slowly, if at all, is a central issue in ensuring the safety of geological isolation of radioactive waste. For repositories in fractured rock masses, as are contemplated in many countries, such demonstration requires a good understanding of the scientific principles governing radionuclide transport in fractures and the availability of techniques to characterize the fracture networks in specific rock masses.

The Stripa Project was an imaginative and pioneering international venture that has made major contributions both to scientific understanding of groundwater flow and solute transport in fractured rock and the development of practical tools and procedures for characterizing and controlling groundwater flow. Scientists in all of the nine participating countries have gained much experience that can now be used to good effect in developing national programmes. Developments and progress at all stages of the thirteen years of investigations have been thoroughly documented in the comprehensive set of technical reports. These provide an invaluable archive for researchers worldwide who will be stimulated to investigate the many issues raised by the Stripa studies. Overall, the Stripa Project is a unique example of a well managed, cost-effective international collaborative project; as such it can serve as a basis upon which to build future projects, both national and international, in the pursuit of safe disposal of radioactive waste.

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APPENDIX 1 – ACRONYMS

AECL	:	Atomic Energy of Canada Limited
ANDRA	:	Agence Nationale pour la gestion des Déchets RAdioactifs (France)
BMT	:	Buffer Mass Test
CEA	:	Commissariat à l'Energie Atomique (France)
CFEST	:	Coupled Fluid, Energy and Solute Transport
DoE	:	Department of the Environment (UK)
DOE	:	Department of Energy (USA)
EDZ	:	Excavation Disturbed Zone
EPM	:	Equivalent Porous Medium
HAG	:	Hydrochemistry Advisory Group
HCB	:	Highly Compacted Bentonite
HLW	:	High-Level Waste
IAEA	:	International Atomic Energy Agency
IVO	:	Imatran Voima Oy (Imatran Power Company – Finland)
JEN	:	Junta de Energia Nuclear (Spain)
JTC	:	Joint Technical Committee
KBS	:	Kärnbränslesäkerhet (Nuclear Fuel Safety – Sweden)
LBL	:	Lawrence Berkeley Laboratory (USA)
NAGRA	:	Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (National Cooperative for the Disposal of Radioactive Waste – Switzerland)
NEA	:	Nuclear Energy Agency
OECD	:	Organisation for Economic Cooperation and Development
PNC	:	Power Reactor and Nuclear Fuel Development Corporation (Japan)
REV	:	Representative Elementary Volume
SAC	:	Swedish – American Cooperative (programme)
SCV	:	Site Characterization and Validation
SGAB	:	Swedish Geological Company

SKB	:	Swedish Nuclear Fuel and Waste Management Company
SKBF	:	Swedish Nuclear Fuel Supply Company (in 1984 SKBF became SKB)
TSG	:	Technical SubGroup
TVO	:	Teollisuuden Voima Oy (Industrial Power Company Ltd – Finland)

APPENDIX 2 – GLOSSARY

Most definitions in this Glossary have been taken from a variety of IAEA glossaries.

absorption: Generally used to refer to ionic exchange reactions taking place largely within the pores of solids, in which case the absorption capacity of the solid is proportional to its volume.

adsorption: Adhesion of ions in a solution to the surface of solids with which they come into contact; hence adsorption capacity of a solid is generally proportional to its specific surface.

backfill: The material used to refill the excavated portions of a repository or of a borehole after waste has been emplaced.

barrier, engineered/natural: A feature which delays or prevents radionuclide migration from the waste and/or repository into its surroundings. An engineered barrier is a feature made by or altered by man; it may be part of the waste package or part of the repository.

bentonite: A soft plastic light-coloured clay formed by chemical alteration of volcanic ash. It is composed essentially of montmorillonite and related minerals of the smectite group. The properties of bentonite depend largely on its ion-exchange characteristics and its ability to swell. Bentonite is ideally suited for use as a buffer material for surrounding waste packages in a deep repository.

bleeding: Separation of water from the cement paste in mortar or concrete. If separation occurs during compaction and the excess water lies on the concrete surface, this can induce good curing; if, however, it occurs after compaction, the water collects underneath the larger aggregate particles and reduces the final strength of the mix.

borehole: A circular hole produced by rotary drilling. Small-diameter boreholes are needed for the investigation of candidate repository sites. Large boreholes can be used for the emplacement of waste packages. Disposal boreholes can be drilled from the surface or from tunnels in a deep mine.

borehole plug: An engineered barrier, usually a cementitious material but also highly compacted bentonite or other clays, used to close a borehole in order to prevent intrusion by water.

buffer material: Any substance, frequently a clay, placed around a waste container in a repository. Often a primary purpose of such material is to serve as an additional barrier to prevent water from contacting the waste container and, by adsorption, to reduce the rate at which radionuclides can migrate from the waste into the repository.

bulkhead: A wall-like structure, made out of stone, steel, concrete or any other plugging material, designed to resist fluid pressure, with the purpose of preventing water from entering a sealed-off portion of a repository.

clay: Minerals that are essentially hydrous aluminum silicates or, occasionally, hydrous magnesium silicates, with sodium, calcium, potassium and magnesium cations. Also denotes a natural material with plastic properties which is essentially a composition of fine to very fine clay particles. Clays differ greatly mineralogically and chemically and, consequently, in their physical properties; especially because of their large specific surface areas, most of them have good sorption characteristics.

crystalline (rock): Term used to describe a rock consisting wholly of crystals or fragments of crystals; especially said of an igneous rock developed through cooling from a molten state and containing no glass, or a metamorphic rock that has undergone recrystallization as a result of temperature and pressure changes. The term may also be applied to certain sedimentary rocks (such as quartzite, some limestones, evaporites) composed entirely of contiguous crystals.

curing: The process of hardening of cementitious materials. For hydraulic cements the processes involve hydration of the constituents.

drift: An underground horizontal passage.

durability (of barrier materials): The resistance of a material to deleterious actions arising from internal, external, chemical, physical and physicochemical forces. Durability parameters can be measured and the material can be characterized on the basis of specified parametric limits.

electrophoresis (also known as electrokinetic treatment): The process by which the particles of a fine particulate grout are encouraged to penetrate thin fissures by means of a direct electrical current.

engineered barrier: See **barrier**.

exchange capacity (usually **cation exchange capacity** or CEC): The total number of equivalents of exchangeable ions contained in a unit weight of a soil or mineral.

far field: Rock formations outside of the repository, including the surrounding strata, at a distance from the waste disposal locations such that, for modelling purposes, the repository may be considered as a single entity, and the effects of individual waste packages are indistinguishable in the effects of the whole.

fault: Fracture or zone of fractures in geological media along which there has been displacement of the two sides relative to one another, generally parallel to the fault plane.

fracture: A crack, joint, fault, or other break in rock. In underground repositories, fractures are of concern as possible paths for water flow and radionuclide migration.

gelling, gellation: Formation of a gel in hydraulic cements and concretes, as well as in chemical and other grouts.

granite: A coarse-grained plutonic rock formed either by slow cooling of a large intrusion of magma (e.g. batholith) or through granitization by transformation of pre-existing country rock. Its mineralogical composition includes quartz (20-40%), alkali feldspar, mica, hornblende and accessory minerals.

grout: A relatively low-viscosity slurry of water, cement and other fine solids. Grouts can be pumped or injected into geological media.

heat-generating waste: Waste that is sufficiently radioactive that the energy of its decay significantly increases the temperature of its surroundings. Spent fuel elements require active cooling – for example, in a water-filled basin – for several years after discharge from the reactor. The heat-generating period of high-level waste and spent fuel in a repository may last several hundred years.

heat of hydration: Heat generated by the exothermic reactions associated with the hydration of cement.

hydraulic conductivity: Ratio of flow velocity to driving force for viscous flow under saturated conditions of a specified liquid in a porous medium.

joints: Small natural fractures or breaks in rock along which no appreciable movement has occurred.

leachability: The susceptibility of a solid material to having its soluble, sorbed and/or suspendable constituents removed by the dissolving or erosive action of water or other fluids.

leaching: *(1)* Extraction of a soluble substance from a solid by a solvent. *(2)* The gradual erosion and/or dissolution of chemical species from a solid. *(3)* The removal of sorbed material from the surface of a solid or porous substance.

longevity (of engineered barriers): The ability of a material to maintain its design performance through time, under the range of temperatures, pressures and geochemical conditions of the host environment.

model: In applied mathematics, an analytical or mathematical representation or quantification of a real system and the ways that phenomena occur within that system. Individual or sub-system models can be combined as system models. Deterministic and probabilistic models are two types of mathematical models.

monomer: A substance consisting of single molecules (see **polymer**).

multibarrier: A system using two or more independent barriers to isolate the waste from the human environment. These systems can include the waste form, the container (canister), other engineered barriers and the emplacement medium and its environment (see **barrier**).

near-field region: The excavated repository including the waste package, filling or sealing materials, and those parts of the host medium where the characteristics have been or could be altered noticeably by the repository or its content.

osmosis: The passage of solvent through a semi-permeable membrane from a diluted solution into a more concentrated one (a semi-permeable membrane allows passage to the molecules of the solvent but not to the molecules of the solute).

packer: Inflatable ring inserted and inflated inside a borehole to seal off a particular length of the hole for special testing or treatment.

paste (cement paste): Mixture of cement and water containing no sand or coarse aggregate. The gel that cements the sand and coarser aggregate particles together in concrete is termed cement paste.

performance assessment: Analysis to predict the performance of the system or subsystem, followed by comparison of the results of such analysis with appropriate standards or criteria. When the system under consideration is the overall waste disposal system and the performance measure is radiological impact or some other global measure of safety, performance assessment becomes the same as safety assessment.

permeability (of rock): The capacity of a porous or pervious rock for transmitting a fluid.

plug: A material such as cement, bentonite, polymers, etc. which can be placed in a drill hole to assist in alignment of the hole during re-entry, to maintain hole integrity, to reduce water inflow into the borehole, etc.

polymer: A material in which the molecule is built up from a series of linked small molecules. The molecular size of the polymer determines its mechanical properties (see **monomer**).

porous medium: Materials that contains voids through which water or gas may flow.

pozzolana: Materials that contain reactive silica capable of reacting with lime to give cementitious products of high durability. The materials can be natural pozzolana, e.g., volcanic ashes or diatomaceous earths, or manmade. Pozzolana are commonly used in concrete mixtures to remove the free lime produced in the hydration of cement.

principal stresses: If a mass or body is loaded by several forces in different directions, the stress system may be resolved into three simple direct stresses which act on planes at right angles to each other. These planes are principal planes and the stresses on these planes are called principal stresses.

quality assurance: Planned and systematic actions aimed at providing adequate confidence that an item of a facility will perform satisfactorily in service.

quality control: Actions that provide a means to control and measure the characteristics of an item, process, facility or person in accordance with quality assurance requirements.

radionuclide migration: The movement of radionuclides through various media as a result of fluid flow and/or by diffusion.

repository: A facility or designated site for storage or disposal of radioactive wastes.

rheological properties: Flow properties of materials, usually defined by some combination of elastic, plastic, and viscous models.

seal: Seals are used in shafts, tunnels, drifts, adits, etc., to close these openings permanently or to reduce or eliminate radionuclide migration out of a repository.

segregation: Segregation of different fractions of a concrete mix when emplaced, transported or dropped. The large particles settle to the bottom, thereby giving a concrete mass of variable strength and consistency.

shaft: An access passage from the surface to the subsurface facilities for men and material, ventilation or waste.

silica fume: A material used to stiffen an area of sand or other loose material. The material usually is a good adsorbent and has high resistance to sulphate attack, as well as good pozzolanic properties.

smooth blasting: Method of rock blasting used in underground excavation when a smooth final rock wall is required. The process involves the detonation of a large number of charges in small-diameter holes drilled along the required rock face after the main charges.

sorption: A broad term referring to reactions taking place within pores or on the surface of a solid. Its use avoids the problem of technical distinction between **absorption** and **adsorption**.

stress (stress fields)**:** *(1)* In common use stress is the force applied to a body divided by the area over which it is applied. It therefore has units of N/m^2 or Pa. *(2)* The stress level is the intensity or value of stress at a particular point in a particular direction. *(3)* The stress field describes the distribution of stresses within a domain. *(4)* Virgin stresses are those existing in the ground before any excavation takes place. *(5) In situ* stresses are those existing in the undisturbed rock rather than in a discrete sample that has been removed.

superplasticizer: A material that can be added to drilling mud; it will provide resistance to flow due to internal friction and the combined effects of adhesion and cohesion. Superplasticizers added to cement will reduce shrinkage at low water/cement ratios and improve the workability of the material.

surveillance: All planned activities performed to ensure that conditions at a nuclear installation remain within the prescribed limits. For a waste repository, surveillance may continue past the periods of operation and closure.

validation: Validation is a process carried out by comparing model predictions with independent field observations and experimental measurements. A model cannot be considered validated until sufficient testing has been performed to ensure an acceptable level of predictive accuracy.

validation (as used in the Stripa Project): Validation of a model, in a given application, consists in determining, by appropriate measures, that it provides a representation of the process or system that is acceptable to an assembled group of knowledgeable experts.

verification: A mathematical model, or the corresponding computer code, is verified when it is shown that the code behaves as intended, i.e. that it is a proper mathematical representation of the conceptual model and that the equations are correctly encoded and solved.

water of crystallization: Water molecules trapped or incorporated in a crystal lattice during the crystallization process. The water usually can be driven off by heating to a high temperature.